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E. P. Lewis.

LIGHT

A COURSE OF EXPERIMENTAL OPTICS

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EXPERIMENTAL OPTICS

CHIEFLY WITH THE LANTERN

BY

LEWIS WRIGHT

AUTHOR OF

"OPTICAL PROJECTION, A TREATISE ON THE USE OF THE LANTERN"

SECOND EDITION, REVISED AND ENLARGED

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"ASSUREDLY there is something in the phenomena of Light; in its universality; in the high office it performs in Creation; in the very hypotheses which have been advanced as to its nature; which powerfully suggests the idea of the *fundamental*, the *primeval*, the antecedent in point of rank and conception to all other products or results of creative power in the physical world. It is LIGHT, and the free communication of it from the remotest regions of the Universe, which alone can give, and does fully give us, the assurance of a uniform and all-pervading Energy—a MECHANISM almost beyond conception complex, minute, and powerful, by which that influence, or rather that movement, is propagated. Our evidence of the existence of gravitation fails us beyond the region of the double stars, or leaves us at best only a presumption amounting to moral conviction in its favour. But the argument for a unity of design and action afforded by Light, stands unweakened by distance, and is co-extensive with the Universe itself."—SIR JOHN HERSCHEL.

Gift of Prof E.P. Lewis

First Edition, 1882. *Second*, 1892.

PREFACE TO THE SECOND EDITION

At the Annual Meeting in 1882 of the Teachers' Training and Education Society, Professor Huxley remarked upon the great difference between two kinds of "what persons called knowledge." "That which they had constantly to contend against in the teaching of science," he said, "was, that many teachers had no conception of that distinction; for they thought it quite sufficient to be able to repeat a number of scientific propositions and to get their pupils to repeat them as accurately as they themselves did. . . . . . The teacher should be instructed that his business in teaching was to convey clear and vivid impressions of the *body of facts* upon which the conclusions drawn from those facts were based." To do this in some degree for one branch of Physics was the original object of this unpretending little work; which aimed rather at being a companion and supplement to the already existing text-books, than anything else. No "formulæ" will be found in it; but I have merely tried to place clearly before the mind of the reader, through something like a complete course of actual experiments, the *physical realities* which underlie the phenomena of Light and Colour.

In regard to the experiments described, there are two things to be said. It would have been desirable, if possible, to have stated the originator of every experiment; but it was not possible. Some arrangements are, to the best of my belief, original; but none are put forth as such except the few expressly stated, and it should be perfectly understood that no personal claim is implied regarding other experiments because no credit is given to some one else. The absence of such credit is simply due to the difficulty of obtaining information concerning these matters.

The second remark is, that the order of the experiments differs considerably in some cases from that usually adopted. Such is the result of considerable reflection, and of a belief that the order chosen is, upon the whole, best adapted to the primary end of assisting vivid conception of the physical realities considered, and *the relation of the phenomena to one another.* The same may be said as to the brief references made to the connection between the phenomena of Light and the problems of Molecular Physics. Brief as they are, it is hoped that they may in some minds excite a real interest in those problems, and deepen that sense of the *reality* of the phenomena which is so desirable.

In a course of experiments in Physical Optics, projection upon a screen is not only far superior in general effect to any other method of demonstration, besides having the advantage of exhibiting the phenomena to the whole of a class or audience at the same time, but has another recommendation of primary importance. The trained physicist well understands the meaning of what is visible to him solely through his lens, prism, or other apparatus; but the scholar new to the subject finds it difficult to interpret in terms of physical phenomena what thus appeals merely to his own visual impressions. When he looks through a prism, for instance, it is difficult for him to get rid of a vague notion that "something in the prism" colours what he sees. But when the rays of light are projected through the prism, and the colours appear on the screen *apart from himself*, as it were, he cannot help understanding that what thus appears to others at the same moment as to him is a physical reality which he has to trace out, and must learn to understand in physical terms. What is meant will be readily understood by any science-teacher.

Hence the method of experiment chiefly adopted here, for which all science-teachers and students are deeply indebted to Professor Tyndall, who carried lantern demonstration to an extent and perfection never before attained. The magnificent apparatus of the Royal Institution, however, appears to have created an impression that electric cameras and other very costly appliances are necessary for effective work of this class; whereas the greater number of experiments can be shown satisfactorily to at least a science class with even a good gas burner; while any good lantern can be made at small expense a very efficient piece of apparatus. To make this also clear, and thus induce many teachers to substitute the most perfect kind of demonstration for far less striking methods, or for mere diagrams, was a second object of these pages.

At the same time I have not forgotten the solitary student, and have tried not only to give sufficient hints for him to make most of the experiments without lantern or other bulky apparatus, but especially to find abundant *manual work* for him, more particularly in the fascinating domain of polariscope phenomena. What indeed led me first to hope that room might be found for such a work as this, was the recollection of how much my own delight in the experimental study of Optics had been due to the personal help and teaching of a few individuals. To the Rev. Philip R. Sleeman, F.R.A.S., F.R.M.S., I had in particular been indebted not only before the first edition of this little book was thought of, but have been since, for many references to foreign papers and memoirs, and many "detached" items of information which only his wide and general acquaintance with the Continental treatment of Physical Optics could have supplied. And to Mr. C. J. Fox, F.R.M.S., I owed my first practical introduction to that mica-film work, which I hope others may find as attractive as I have done, and which so admirably illustrates the phenomena of polarised light. But for these two friends, some of the most acceptable among the following pages would never have been written.

Such were the aims with which the first edition of this work was prepared; and it has been a great and unexpected gratification to find how considerably they have been realised, and how much such a course of Experimental Optics appears to have been really needed. Of the numerous letters received, a great many, from all sorts of readers, have been of a positively *enthusiastic* character which was a surprise to me, and is probably not very common concerning books of any kind upon any branch of Physics. From University lecturers and graduates, to hard-worked science teachers and solitary students, have such letters been received; and it has been a source of peculiar pleasure to learn that in some cases a clearer appreciation of beautiful physical phenomena, gathered from this work, has awakened an enthusiasm previously quite lacking concerning that mathematical treatment of them, from which its own pages have been sedulously kept free.

The present edition is somewhat enlarged, and in some respects modified. Further consideration has led me to revise the method and order of treatment as regards some of the phenomena of Polarised Light; and criticisms of value regarding other points of the subject, by Professors A. W. Reinold and S. P. Thompson, have gladly had regard paid to them in the present work. Some attempt has been made, though briefly, to show the general relation and bearing of recent discoveries by Hertz, Lippmann, and others. Having also received many proofs of the delight and instruction afforded by the beautiful mica polarising preparations first devised by Mr. C. J. Fox, and having carried the designing and preparation of such illustrations very much farther since this work originally appeared, I have added full details of everything of the kind devised to the present date, and of the practical manipulation of mica films. These paragraphs will constitute perhaps the principal additions in the following pages.

But aim and method remain the same. This is not a text-book, or intended as such. In spite of pressing requests so to extend the treatment as to give it somewhat more of that character, I adhere for many reasons to its original idea, and confine the theoretical explanation to diagrams and familiar mechanical analogies, couched in language which it has been endeavoured to make most simple and clear. There are abundance of most excellent text-books, amongst which Preston's *Theory of Light*, published quite recently, may be specially mentioned for its elegance of treatment and simplicity of arrangement. The aim of this little book is simply and solely to give such a clear conceptual grasp of the chief *facts* in Physical Optics, as may *make the text-books real.*

I only add a few words respecting the last chapter, concerning the propriety of which a great difference of opinion has been expressed. As observed in the former Preface, the irresistible propensity to go beneath the surface and search for the hidden essence of things, has been felt and manifested not only by all our leading physicists, but by all who have had any vivid impressions of the mysteries surrounding them. The extract from Sir John Herschel which prefaces the volume, shows this tendency very strongly. So have I also uttered my thoughts; it is believed without dogmatism, while there is not the slightest danger that the name of the author will give, as in some instances, any factitious weight to them. For such utterance there is no need of apology. But it does seem worth while to note the curious fact, that while these thoughts of mine have, as I find, been read with interest and received with respect by many interested (some few even distinguished) in mathematics and physics, certain scornful sneers and expressions of condemnation which have also not been lacking, have so far been traceable in every instance known to me to the adherents of a certain school of biology! It appears to me rather remarkable that this attitude of mind towards such thoughts should be specially developed in a class of students and teachers whose acquaintance with physics is not, as a rule, very great and who deal largely with hypotheses and generalisations not capable as yet of very precise verification; whilst men who really are conversant with the mathematically exact operation of definite physical law, feel as a rule no such antagonism. Without further remark, however, I here again leave both the chapter and the work itself to the judgment of the reader.

A large number of the experiments here described appeared originally as a series of articles in *The English Mechanic.* I am indebted to the proprietors of that journal for their free permission not only to use the text of the articles in any way thought best, but also the diagrams by which they were illustrated. I am further indebted to Messrs. Longman & Co., for permission to use certain of the diagrams in my work upon *Optical Projection*, published by them.

LONDON, *April* 18, 1892.

CONTENTS

CHAPTER I

THE LANTERN AND ACCESSORY APPARATUS

CHAPTER II

RAYS AND IMAGES.—REFLECTION

CHAPTER III

REFRACTION.—TOTAL REFLECTION.—PRISMS AND LENSES.

CHAPTER XI

POLARISING APPARATUS

CHAPTER XII

CHROMATIC PHENOMENA OF PLANE-POLARISED LIGHT.—LIGHT AS AN ANALYSER OF MOLECULAR CONDITION

APPENDIX TO CHAPTER XII

CHAPTER XIII

CIRCULAR, ELLIPTIC, AND ROTARY POLARISATION

CHAPTER X

OPTICAL PHENOMENA OF CRYSTALS IN CONVERGENT POLARISED LIGHT

CHAPTER XV

POLARISATION AND COLOUR OF THE SKY.—POLARISATION BY SMALL PARTICLES

CHAPTER XVI

FULL-PAGE PLATES

LIGHT

CHAPTER I

THE LANTERN AND ACCESSORY APPARATUS

The Lantern—The Optical Objective—Pencil attachment—Various Radiants—Oxyhydrogen and Arc lights—Centering the Radiant—Mounting and manipulation of the Lantern—Accessory Apparatus—Screens—Vertical Work—Importance of Darkness.

1. **The Lantern.**—Any fairly good lantern will serve to perform the following experiments, provided the "front" is so made as to slide on and off a flange-nozzle. This is usual with the better brass fronts made with lengthening tubes, but not with fronts half brass and half tin; and in the latter case the alteration should be made, so that either the ordinary objective, or the optical objective to be presently described, or any other apparatus, will slide on and off at pleasure. The ordinary objective will be occasionally wanted to exhibit diagrams, while the other will be placed on the nozzle for experiments: the lantern will also be available for all ordinary purposes. A bi-unial is exceedingly convenient, as the top lantern may be used for diagrams, while the lower nozzle carries the optical objective. Any of the usual forms of condensers will suffice. My own bi-unial is mounted on four short brass pillars, in order to introduce conveniently a Bunsen burner or other apparatus for coloured flames into the bottom lantern if required.

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2. **Optical Objective.**—The ordinary objective used for exhibiting slides would suffice more or less perfectly for many experiments; but a special optical objective is almost necessary for many, and preferable for nearly all. It is, moreover, absolutely necessary for the polariscope to be hereafter described; and, as the same lenses and fittings answer for both, and are of a very inexpensive character, it is more satisfactory to provide for efficiency at the outset. The ordinary slide-stage is also unduly large for the insertion of the necessary apertures, slits, or other apparatus, besides being inconveniently situated for manipulation; and the large field is a great waste of light for many experiments which need all we can use. Supposing, for instance, a rather small aperture has to be diffracted, we can condense no light upon it in the ordinary slide-stage; whereas by bringing it a few inches out in front, we can insert an additional convex lens, mounted in a wooden frame *as a slide*, in the ordinary stage, and so condense a very large portion of the full beam upon the aperture.

The arrangement recommended for the optical objective is shown in Fig. 1. A B is a nozzle (of japanned tin or brass, according to the style of the lantern), which slides nicely on the lantern nozzle, and is kept from rotating by a slot and pin. We will suppose it 3½ inches diameter, for 3½-inch condensers. B C is a 3-inch brass tube 3 inches long, which should screw into a collar at B, as it will be required to unscrew from this into the polariscope elbow, to be hereafter described. Near the bottom or lantern end a square aperture, K, is cut through both sides to form a slide-stage, which should "take" slides an inch thick, and 2¼ inches wide. The slides are kept down to the bottom end by a circular L-shaped collar, L, operated by studs working in longitudinal slits as usual, and forced against the slides by a spiral wire spring M, abutting against the collar at C, which screws into the other end of the tube, and has screwed into it the jacket D of the focusing tube, with its rack and pinion E. The focusing or lens tube F will be about 2¼ inches in diameter, and has screwed into it at the back end the cell of the plano-convex lens G of 5 inches focus, with the plane side towards the slide-stage. At the other end screws on a collar in which is fixed the nozzle N, projecting outwards from the front flange or collar a clear half-inch, and about 1⅝ inches in diameter. Into the back end of this screws the lens H of 8 inches focus, which may either be a plano-convex,

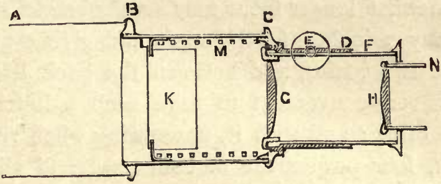

Fig. 1.—Optical Objective.

or of a slightly meniscus form, the whole being arranged so that the lenses are 2¾ inches apart. The focusing jacket should be so adjusted that when the tube is run right out the lenses will focus any slide in K at a short screen distance, and have a backward travel of about 1½ inches.

It will be seen that the lenses are of a very inexpensive character; but such an arrangement is as good as can be adopted, and loses little light. It is the proper arrangement for the polariscope, for which it answers admirably; and it gives a fairly flat field with but little colour. A rack and pinion is by no means essential: indeed, if the sliding tubes are accurately circular and fit well, a plain sliding tube is preferable, in order that the lenses may be removed at pleasure and slits used with parallel light only, or other appliances (such as an adjustable slit or revolving diaphragm) slid into the tube. I have, however, found a really well-fitted plain "draw-tube" by no means so common among ordinary opticians, on this scale, as a fair rack movement. A polariscope with such an objective as is here described can now be purchased for a very few guineas, complete, as described in a future chapter; and in that case nothing more will be necessary than to provide the additional tin or brass nozzle A B, into which the objective of the polariscope, when unscrewed from its elbow, will fit, and constitute the objective for straight work. The equivalent focus of the two lenses is about 3¼ inches, and this will give suitable discs for average screen distances. If the general working distance is long, say from 20 to 25 feet, or more, a somewhat longer focus may be preferable, making the back lens say 7 inches focal length, and giving more space between the two lenses, and between the back lens and the stage. It is very convenient to have such a lower power as well as the other; and with it, unscrewing when required the front lens H, four powers are at command, and all easily adjusted by inserting at C, if necessary, a short screwed tube or "lengthening adapter."

3. **Pencil Attachment.**—There is another front, not by any means necessary, but which I have myself found very useful in certain experiments wherein it is desirable, without the arc light, to obtain an approximately parallel pencil or beam of light of smaller diameter than the condensers, as brilliant as possible. This may be effected by a pair of lenses arranged as in Fig. 2, the convex lens contracting the rays, and the concave re-parallelising them. Fig. 2 is a small-sized system, on which the rays from the condensers are slightly converged to begin with, and parallelised into a pencil about ¾-inch diameter (the parallelism being however only approximate). Such a pencil will add much effect to a Lissajous' figure, as in Fig. 29, or the projection from a

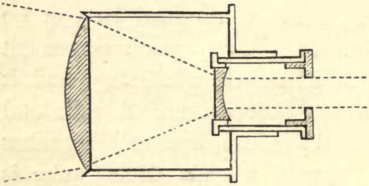

FIG. 2.—Pencil Attachment.

Barton's button. A larger system, with the convex lens of full diameter, so adjusted that when the condensers give a parallel beam and the attachment is inserted, the beam is condensed into about 2 inches diameter, may be of service for polariscope projections. The arc light of course needs no such condensation.

4. **Light.**—Sufficient effects for a class-room or moderate-sized drawing-room may be obtained in nearly all the following experiments[1] from a *good Argand gas-burner.* A class or a few spectators do not need to see the phenomena on a large scale, and by employing a small disc at a screen distance of 5 or 6 feet, very good results may be got in this way. The lantern becomes hot with such a light; but the convenience of being able to get it into work at a moment's notice, and without any apparatus, is very great. A good "Silber" or one of Sugg's best "London" patterns, may be employed, and either gives a very white light of from 22 to 28 candles. Such a burner costs about 6*s.* 6*d.* An Argand burner is best fixed in a lantern by having a slide-tray with an upright pin at the back end, as for the lime-light. Over this pin should slide a socket brazed on a tube, with tap and nozzle on the back end as usual, while a plain elbow at the other end carries the burner. The lime-light, or plain gas, can then be used as convenient, gas sufficing to "work out" privately, at a minimum cost and trouble, almost any desired experiment, even when a more brilliant light is required for public repetition of it. The greater part of the experimental work following has been thus "roughed out" in the first instance.

The brilliant mineral oil lamps give better effects than gas, ranging in power from 50 to as high as 90 candles, that is, *standard* or "gas" candles, there being a looseness about some opticians' estimates (due to taking any candles as tests) which is not desirable. The *triple* forms of wick, of which there are several, are much to be preferred for optical work: the double

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[1] The exceptions are chiefly such as require a *parallel* beam, and are for the most part noted especially.

wicks are apt to give a comparatively darkish streak up the centre of the screen. This is little observable in exhibiting painted slides; but in optical experiments is just where we can least afford any deficiency. Four-wick lamps give as much as 120 candles; but the heat is excessive, and in most cases a three-wick lamp is preferable for optical work.

5. **The Lime-light.**—The lime-light is, however, strongly to be preferred if possible, the effect being so infinitely superior, not only in brilliance, but in *whiteness*, or completeness in the spectral colours. It is not an expensive light either, after the first purchase of the apparatus. Potassic chlorate is now cheaper than formerly, and can be purchased in most large towns at from 7*d.* to 9*d.* per pound; black oxide of manganese at about 2*d.* per pound. At these prices, if the oxygen is home-made, the lime-light for two hours will only cost about 2*s.* 6*d.* besides wear and tear; which is very little for the effect produced. The ordinary details of lime-light lantern management can be learnt in hand-books obtainable from any optician; but it may be well to give a few brief hints on definite points.[1]

The lime-light has three main forms, most properly described as (1) the spirit-lamp jet, (2) the gas "blow-through" jet, and (3) the gas "mixed" jet. The first will give from 100 to 120 candles, and is sufficient for small lecture-rooms or halls: the second will give from 140 to 250 candles: the last 350 to 900 candles, according to the pressure. All alike require a supply of *oxygen* gas, supplied to the jet under pressure. If it is supplied from a bag, this bag should measure 36 × 24 × 24 inches, and *not less*, for optical purposes; if there is no assistant to turn off the oxygen when not wanted, it had better be a little more for any lecture work. The size named is no more than

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[1] I have treated fully of the details of various forms of lanterns, and their practical manipulation, including many particulars not to be found in other sources of information, and with special fulness as regards the lime-light in all its forms, in *Optical Projection: a Treatise on the Use of the Lantern in Exhibition and Scientific Demonstration* (London: Longmans and Co.).

sufficient, with comfortable margin, for two hours' experiment; and some is often wanted for preliminary adjustments. Only the best bags are worth having, and such will last for years if the gas is properly purified, and all taps or metal fittings cleaned and oiled every now and then.

Proper purification, if the gas is home-made, will require passing through *two* wash bottles filled with weak solution of potash or soda. But lime-light work has been revolutionized by the recent great cheapening of compressed oxygen in steel cylinders, effected by the Brin process of manufacture, and the introduction of regulators which keep the pressure at the jet uniform and steady. The cost has been reduced to 4*d.* per cubic foot, and sometimes less, compressed house gas being supplied at the same price; and a couple of cylinders give the most powerful form of light with a minimum of trouble. A single cylinder, with gas from a main, works a blow-through jet without any bag; and even where bags are used to save the cost of compressed house-gas for the mixed jet, the oxygen is often bought in a cylinder, from which the bag is filled, to save the trouble of making. Beard's regulators are perfectly effective in maintaining a uniform pressure.

In some institutions, economy will be secured, with convenience and efficiency, by making oxygen in quantity, and filling metal gasometers, one with this and another with house-gas, to be weighted and used as required.

There is not very much variation in spirit jets; but blow-through jets differ widely, and are certainly capable of improvement. The prevalent fault is too large an opening for the house-gas, which heats the lantern very unnecessarily. The best of the ordinary forms is probably that shown in Fig. 3, the oxygen nozzle O being somewhat below the gas nozzle H, giving a better mixture, with a smaller and more pointed flame. Such a jet should be selected with the outer aperture

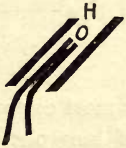

FIG. 3.

as small as possible, and an inclination of about 45 degrees. By fitting an adjustable dome with a smaller aperture over the hydrogen nozzle, this jet assumes a partially "mixed" character, with a better light.

I strongly advise the "mixed" jet where possible, and there is really no danger with it in intelligent hands, especially with gas in cylinders. The power of this jet varies enormously. I devoted much experiment to the subject, and have finally adopted for the mixing-chamber the construction shown in Fig. 4, the chamber being tapered at top and bottom, and packed with alternate discs pierced as drawn, and separated by rings. This gives a perfect mixture, and silence at good pressure. With a nipple of $\frac{1}{12}$ inch bore, it has given occasionally as high as 1000 candles, and can be depended on for 800 candles. It is most conveniently mounted as shown in Fig. 5, with a spiral of long pitch for raising the lime, and a "cut-off" devised by Mr. Andrew Pringle, which allows it to be turned down to a small blue flame, without altering the precise adjustment of the two gases.

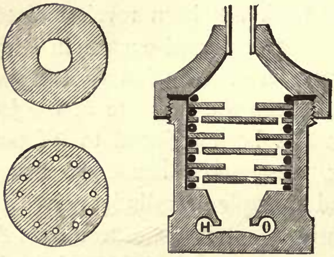

FIG. 4.—Packing for Jet.

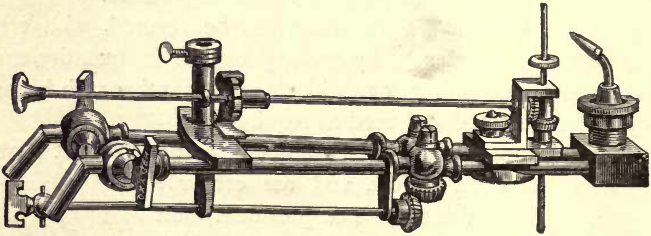

FIG. 5.—Jet with Pringle's Cut-off.

When there is a good pressure—say 2 inches—of gas from the main, the "mixed" jet can be employed with only one bag or cylinder (of oxygen), but requires care and some experience. It will give a smaller radiant spot than the blow-through form, and more light, with less heat and less consumption of gas. If a bag is used in this way it should be lightly weighted with only 56 lbs.; and with a blow-through jet 28 lbs. is sufficient at first, adding another weight when half empty. Two bags with the mixed jet should not have less than 112 lbs., and for a really powerful light three 56 lb. weights should be used, with a fourth to finish. Cylinders give still greater pressure and the best light; but more should not be used (controlling the gas by the taps of the jet) than brings the jet to a very slight hissing, or the verge of it. Pressure is reckoned as gas companies do, in "inches," measured by a U-tube as in Fig 6. The tube is open at one end, while the gas is led to the other by a small tube in a rubber stopper. A wooden scale between the legs of the tube has a line across the middle as a zero point, above and below which on opposite sides it is divided into inches and tenths. Water is poured in up to the zero point; and when the gas is turned on, the pressure depresses the water in that limb and raises it in the other, the *difference* giving the pressure—thus a depression of three inches in the gas-limb really means a pressure of six inches. Nine inches will give an excellent light, but 14 inches may be used if the most which a really powerful jet is capable of is required.

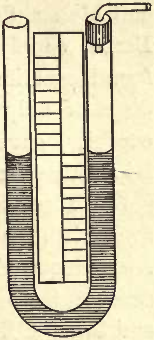

FIG. 6.

The jet must be carefully adjusted by the taps so as to give the utmost light upon the screen; and the distance of the lime from the orifice—averaging about $\frac{1}{8}$ inch with a mixed jet—should also be carefully determined by that test. One advantage of cylinders and regulators is, that when all these adjustments have been made, they can be retained with certainty throughout the experiments, leaving the demonstrator free (beyond turning the jet on and off as required) to give attention to the experimental details.

Soft limes suffice for spirit and blow-through jets; but for the mixed jet the very hardest are required, and the lime will have to be turned a little, keeping the same direction, every minute or two; otherwise deep cavities will be worn in its surface, which spoils the light and may crack the condenser. Zirconia discs do not pit in this way, but unfortunately give a much inferior light to lime. I have, notwithstanding, found such refractory discs very convenient where great brilliance is not required, owing to the fact that no attention is required by them; and Messrs. Schmidt and Haensch, of 4 Stallschreiber Strasse, Berlin, supply them mounted in platinum at 10*s.* each. I found experimentally, however, that the very same material in discs of only half the thickness and without any platinum capsules, gave a considerably better light; and it is to be hoped that ere long such thin plates may be obtainable.

6. **The Electric Light.**—Where suitable current is available (it will range from three to six ampères, and the E.M.F. required will be from 35 to 55 volts) a form of incandescent lamp made specially for lantern use by the Edison and Swan Co. (cost 10*s.* each) will be found very convenient. It can be had either of about 50 candles or 100 candles power.

Of course the arc-light distances in brilliancy all other competitors whatever; but the *two* luminous carbon points were till recently a formidable objection. For years I endeavoured to induce makers of various small lamps to remedy this defect, by abandoning vertical in favour of inclined carbons, as in various "projector" lamps used in the navy; but without success, until Mr. Brockie undertook thus to modify and Messrs. Johnson and Phillips to construct, a beautifully simple lamp which the former had already made for a lantern, with vertical carbons.

The lamp thus modified is shown in Fig. 7, and is so far the best for optical use with which I am acquainted. It is compact, but stands firmly; is very easy to manage, and so steady that I have seen it work for two hours with hardly a blink; and it has answered the severe requirements of the projection microscope with high (immersion) powers. It will also work with considerable range of current, the same lamp working with 7 to 20 ampères.

The effect of inclining the carbons is shown in Fig. 8. The lower carbon is the negative (this lamp needs of course a continuous current), which is set more or less in front of the other according to the length of arc. This brings the "crater" of the positive carbon towards the front, while the incandescence of the lower carbon is brought behind and invisible from the front. Hence the radiation towards the condenser is confined, as in the figure, to that from the crater, while that is much more direct and powerful; and we have that indispensable necessity for the finest optical work—*one single radiant point.*

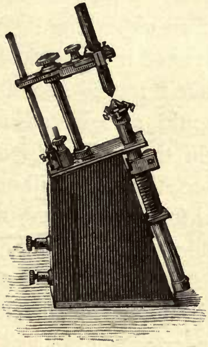

FIG. 7.

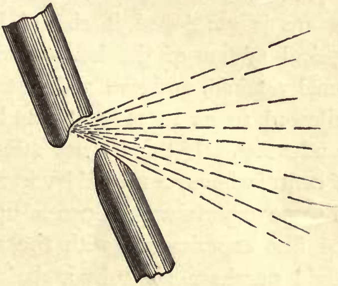

FIG. 8.

To use such a lamp to the greatest advantage, it should be mounted on a table with three rectangular screw motions as in a slide-rest. The most complete and powerful optical apparatus known to me is a circular electric lantern so furnished, the lantern itself being equipped with three equidistant nozzles; such as has been constructed by Messrs. Newton & Co. for the Royal Institution. Either of the three nozzles can by a motion of the hand be brought to the front for projection; and the three can be variously fitted up with any appliances desired. But a lantern of this character is not at all necessary for even a most satisfactory programme of experiments in physical optics, except that the arc lamp must be admitted to be far better suited than any other, for obvious reasons, for the production of spectra.

7. **Centering the Radiant.**—When either the lime-light or arc is employed, it should be adjusted in the axis of the optical system of the lantern with much more care than is usually taken, and the sliding tray should also be accurately adjusted so as to move to and fro in the optic axis of the condensers. If this be not attended to, the light will get out of centre whenever moved backwards or forwards. Very much, in some experiments, depends upon this. We may very often see fine experiments, with the most costly apparatus money could purchase, spoilt by a dark patch upon the screen, and thus worse rendered than a careful operator would have done with a plain "blow-through" jet. This latter, well managed, is in fact amply sufficient for nearly all purposes. With lamps, very accurate centering is of less importance, owing to the larger luminous surface.

Whatever the light employed, we term the original source, in the lantern, the "radiant."

8. **Mounting and Using the Lantern.**—This is very conveniently done upon a small revolving wooden tripod stand like Fig. 9. The top circle turns upon a centre-screw passing through the under one, by which it can be tightened from beneath in any angular position, the total height being from 6 inches to 10 inches, and the lantern fixed to the top in any convenient manner. This being placed on a good-

sized table, the lantern is conveniently raised, and easily turned in any direction, while the large table is available for accessory apparatus.

It is better to extend the revolving top on one side by a *board* A B (Fig. 10) extending out in front (of course with a supporting leg) about 3 feet, furnished with a cross-board C D which can be slid backwards or forwards to any distance from the lantern. The advantage of this plan is, that when a slit or anything else has been properly focused, and the rest adjusted, the whole arrangement can be deflected off at any desired angle for refraction or reflection, without having to readjust the apparatus. Or if we are projecting a soap-film as in § 103, this will be arranged on A B at 45° so as to reflect the light to the screen when the lantern is deflected, and the transverse board C D is adjusted so as to give a base for the focusing-lens F in Fig. 103.

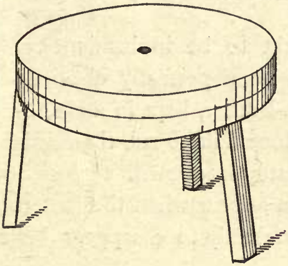

FIG. 9.

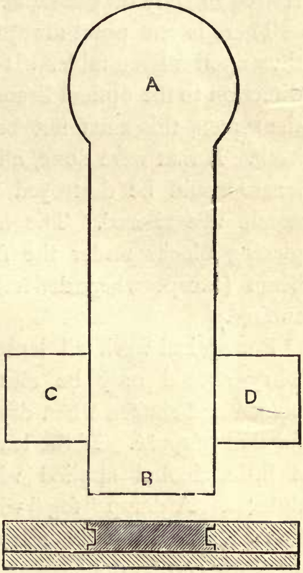

FIG. 10.

The revolving stand may usually be of smooth hard wood, black-leaded on the rubbing surfaces. If the lantern is very heavy, the greatest ease in turning can be secured at some extra expense, by letting metal circles with grooves run upon some bicycle balls. Should the lantern be mounted on short pillars like my own, even short legs may raise the stand too high from the table, and for them may be substituted pads of vulcanized rubber, just to "bite," the lower plate otherwise resting directly on the table.

There is one point always to keep in mind when working thus upon a large table. If it is necessary to give an upward direction to the optical beam in order to get a good position on the screen, this must not be done by canting up the lantern itself. If that were done, all vertical adjustments of prisms and lenses would be destroyed whenever their distance from the nozzle was altered. The *whole table* must be canted up by placing blocks under the front pair of legs, and the optical beam (except when deflected purposely) kept parallel to its surface.

For optical work all lenses ought to be in brilliant order. They should only be cleaned with a perfectly clean (well beaten and shaken when dry) wash-leather, kept in a clean box for that purpose. If the leather alone fails to rub them bright, a little alcohol applied with cotton-wool will remove the dulness. A damp "fog" will often appear when the lantern is first lit, and must be allowed gradually to disappear before anything can be done.

9. **Accessory Apparatus.**—What is needed for special experiments will be described in the proper places; but some accessories will be in almost constant demand. First of all will be required two pillar or rod-stands, made by screwing or casting a half-inch brass tube neatly plugged at the top into a heavy foot of lead or iron, which should have baize glued on the bottom to prevent slipping. Such can be bought at gas-fitting shops for three or four shillings each. On these should slide closely the sockets shown in Fig. 11, into which are screwed or brazed the small tubes B C, which receive the various pieces of apparatus. As it is sometimes necessary to get well *over*

some other article, there should be a few of these, with the length B C various; and if the weight and leverage are too great for the stand, another socket bearing a leaden weight as counterpoise will keep all steady. Or the pillar may be fixed in one end of an oblong foot. In the socket tube itself, small holes, A A, are bored, and saw-cuts made down to them, when a slight pinch together of the two semi-circles so divided, at each end, will make an admirable tight *sliding* fixture, independent of screws or any such nuisance.

Into these sockets we can fit anything. Loose focusing lenses, which will be constantly needed, can be fixed by three short pins, as at A, into a circular hole, turned with a ledge in a disc of wood, B (Fig. 12), into the edge of which is driven a short length of tube, C, fitting into the socket tube B C (Fig. 11). Or if there is no lathe at command, the hole may be cut with a fret-saw, and the lens fixed with short pins at each side. It can be bought mounted in brass if preferred; but in that case it is well, when using, to put round it a border of black card, or have it mounted with one of tin, to exclude from the screen all but the rays focused. A lens of 4 inches diameter and 8 inches focus is very suitable, and a meniscus, with the concave side to the screen, is to be preferred where

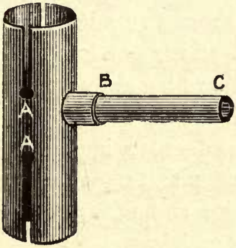

FIG. 11.

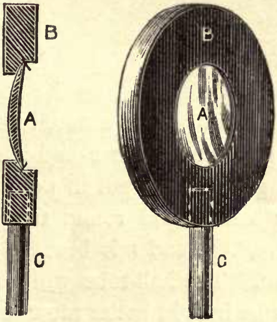

FIG. 12.

the expense of an achromatic lens is an object; but two lenses of 7 inches and 12 inches are very handy, according as we may want to enlarge and collect all the light we can from a small object, or to focus a large one. Quarter-inch tube is a good size for these accessories, but a gauge should be chosen which can be matched, and a foot or two of tube to mount any odd apparatus always be at hand.

A reflector, say 6 inches by 4 inches, of good thin looking-glass, may be mounted as in Fig. 13. D B is a length of the tubing, D C fitting into the socket. From A to B half the tube is filed away, with a notch at C, into which one long edge of the glass fits. The B end is still further filed away; and when the glass A B is put in position, with a strip of card or blotting behind and round the bearing edges, to impart a little "give," the end B is brought over, and B and C gently pinched down. The half-tube will keep it nice and stiff. A reflector may be bought better mounted of the opticians.

FIG. 13.

A glass prism, 2 inches long, and about 1¼ inches in face, of good dispersive power, can be bought for about 7*s.* 6*d.*, and is mounted as in Fig. 14, the tube being fixed into a regular cast socket, or one made of sheet brass turned up ¼ inch. Into this the end of the prism is cemented. Of course, such a prism

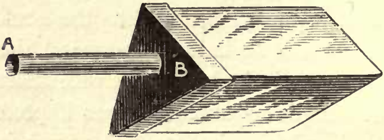

FIG. 14.

is not "optically" faced, only polished like lustres; but it is good enough for most screen work. In the socket, Fig. 11, it can be set and turned to any angle horizontally; but another socket should be provided, as in Fig. 15, bearing a piece of brass, A B, at the end, in which is bored, perpendicularly, a hole of the regular socket gauge. In this the prism can be turned to any angle vertically.

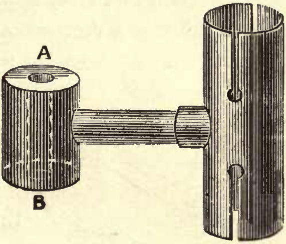

FIG. 15

For spectrum work a prism bottle filled with bisulphide of carbon is far to be preferred, giving nearly double the dispersion of any ordinary glass prism. Phenyl-thiocarbimide is still better, having as much dispersion as carbon bisulphide, with considerably less volatility and odour, so that bottles of it can be used with much less caution. Such prisms can, however, only be used vertically, and a glass one is handy for some other positions sometimes necessary.

These fittings are recommended because they can be adjusted in work with such ease, precision, and rapidity, and are so readily interchangeable in all sorts of combinations. In these respects they are far superior to the usual methods of mounting focusing-lens, prisms, &c., each on the top of a special stand, besides being much cheaper, and easier made.

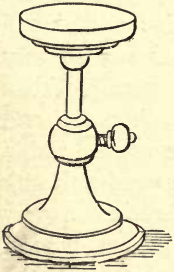

FIG. 16.

An adjustable table-stand somewhat resembling Fig. 16 will be needed for many things. The handiest size for average work, with such a tripod as Fig. 9, is one which will rise from 12 to 18 inches, with a top about 6 inches across. Some kind of adjustable clip will also be needed to hold wires, cards, plates, &c. The best construction for all purposes is what is known as the "Bunsen universal holder," shown in Fig. 17. The clip itself can either be inserted vertically into the pillar-socket, or the intermediate joint will allow of any angle or other variety of position. The price of each of these, if purchased, will be about 6*s.*

A cardboard screen about a foot square should be provided, though it is not actually necessary. It is easily and cheaply made by screwing or glueing an inch wooden rod or ruler into any wooden foot, sawing down the middle from the top about three inches, and sticking the edge of a thick sheet of cardboard in the slit. The centre should be the same height as the lantern objective from the operating table; and if one side of the card is white and the other blacked, it will serve either to stop light when required, or to receive an image.

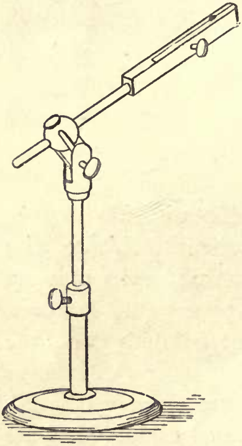
FIG. 17.—Bunsen Holder.

Various blackened cards or thin zinc plates, each 4 inches by 2¼ inches, will also be required, in which to cut suitable apertures for insertion in the optical stage. The zinc also should be blackened if used. An excellent optical black varnish may be made by mixing "vegetable" black at discretion with a mixture (about half and half) of ordinary French polish and methylated spirit. On small work it should be applied with a large camel's hair or other soft brush; on large woodwork with a paint brush. For this varnish is suitable for almost every purpose, from blacking cards, to large gas-bag pressure-boards. It dries quickly a full dead black, and does not come off, or warp the cards.

10. **Screens.**—Where there is a good white plaster wall, well smoothed, nothing will equal it. Next to that, for small

screens, the best is a single sheet of white paper, for which may be purchased a piece of "continuous drawing cartridge" paper, always procurable 60 inches wide, and sometimes as much as 72 inches. It can be fixed to a wall with drawing-pins, or mounted on a roller. Large screens are made of linen faced with paper. Transparent screens are more convenient in some places; but the operator must in such cases be content with a small disc, in order to avail himself of the best material, which is continuous tracing paper, also procurable 60 inches wide. As transparencies are usually wanted in small space, this is amply large enough. Such paper shows infinitely better than the best wetted sheet, and there is no need whatever of stretching it on a hoop: it is just as well to mount it on a roller. Transparent screens are not, however, so well adapted as an opaque white surface for optical work, especially with the prism; and it is moreover often desirable that an audience or class should see, not only the effect upon the screen, but the experimental means by which it is produced.

For some experiments we may need a horizontal screen over the apparatus, and for this a white ceiling will answer perfectly. We shall have to employ it almost immediately.

11. **Diagrams.**—These can be prepared in many ways, but the following are the best. White diagrams on a black ground may be done with stout needle-points (either compass or ruling points), through photographic black varnish spread thinly and evenly, when firm, but not quite so dry as to be chippy. Or a glass may be warmed and smeared with solid paraffin, which is then cleaned partially off and remelted so as to be as thin and even as possible; if the plate is then held over the smoke of burning camphor this will adhere, and though not so hardy as the other, will bear careful usage, and cuts easier. Compass curves are best struck from small bits of thin horn as centres. These engraved diagrams are very striking; but the darkness of the screen hinders details being pointed out, and it is better therefore to employ blue printer's ink

spread on the plate with a dabber. This allows the shadow of a pointer to be seen, while the white lines are equally distinct. For black lines on a white ground there are also several good methods. The first is to draw with a hard pencil upon the *very finest* ground glass—a process any one can execute at once. Another is to *scratch* with needle-points on a sheet of gelatine, rubbing a little blacklead into the scratches, and mounting the film between two clean glasses. Or a drawing may be made with pen and ink on a photographic chloride plate, or a film of mica, or even on a clean glass plate *licked* over, which keeps the ink from spreading. If some sugar is dissolved in ink thus used, a little powdered lamp-black dusted over the lines will make them much darker.

All diagrams should be faced with glass when completed, and bound with strong dark gummed paper. This edging paper must be gummed very freely and *dried*, the strips being moistened when used. Wet gum, freshly applied, does not adhere to glass with certainty.

12. **Vertical Attachment.**—Though only needed for one or two experiments mentioned in this work, and those not essential ones, a vertical attachment capable of projecting horizontal surfaces is so generally useful in acoustic projections and for other purposes, that a description will be of use. As invented and perfected by Professor Cooke, of Harvard, U.S., it is rather an elaborate piece of apparatus; but all required can be done very simply and cheaply as shown in Fig. 18. A cubica wooden box is open on one of the perpendicular sides, and has a circular aperture cut in the top nearly extending to the edges of the square. The size of the box and of this aperture depend on the size of a field to be projected; for magnetic curves or wave-ripples, a circle of less than five or six inches diameter is of little service. Opposite the open part, on strips of wood at each side, a piece of good plate looking-glass is supported at an angle of 45°, so as to throw the horizontal beam from the lantern up perpendicularly through the circular aperture. Owing to the

larger size of this (the horizontal field) a *diverging* beam will generally be required, from any ordinary lantern, to cover it; and hence there *should* be a large plano-convex lens (costing about 15*s.* for one 6 inches in diameter) fixed to the under side of the aperture, so as to re-converge the rays on the focusing-lens. Fair effects can, however, be procured without this with a good lime-light, in spite of what is then wasted. In any case, all but the condensers are removed from the lantern, and these are so adjusted, and the box so placed in front, that the field is just covered and no more. To one side of the box is fixed a stout perpendicular brass rod or tube, the same gauge as the pillar-stands already described, and furnished with two sockets like Fig. 11. The lower socket bears a focusing-lens, either plain or achromatic—it may be the one already described (Fig. 12)—and the upper socket the plane reflector, which reflects the image to the screen. These two sockets must, of course, be fitted to the apparatus, as it is necessary that the lengths B C (Fig. 11) should in this case be such as to bring the lens and reflector central with the vertical optic axis; but the lens and mirror already described will answer for the rest. It might be supposed that the first surface of the mirror would cause a double image on the screen; but it is so faint in comparison with the other, that any such effect is rarely perceivable at all, and only then to close and special observation.

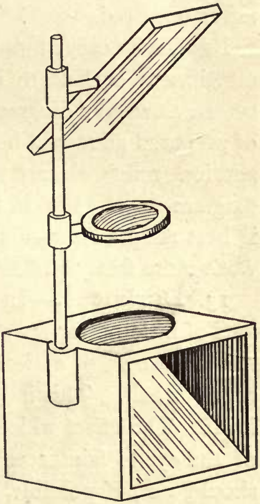
FIG. 18.—Vertical Attachment.

Messrs. Newton & Co. have constructed a bi-unial for scientific purposes, of which the top lantern tilts backwards on a hinge, so that its optical system points vertically upwards, a reflecting mirror being added above. This device avoids any loss of time or light in making adjustments, giving a good vertical projection instantly when required. It is of course only practicable with the lime-light and mixed jet, which must not be turned off while the lantern is vertical, or the free hydrogen flame will ascend and crack the condenser. With this precaution I found that such an accident (rather to my surprise) never occurred.

Besides its other more strictly experimental uses, the vertical attachment or lantern is very effective for projecting on the screen *extempore* diagrams, which are easily traced on a sheet of prepared glass laid horizontally. It often makes a demonstration much clearer to work out a somewhat complicated diagram step by step in this way. The ground glass and pencil is best adapted for this method of work, as the operator can work more freely and see more precisely what he is doing.

13. **Darkness.**—In all cases, but more especially when radiants of little power are employed, it is of the greatest importance to the success of optical experiments, to secure *darkness* in the room or hall. This is apart from the effect of the experiment itself. The effect which darkness produces upon the sensibility of the eye to fainter effects is marvellous, and this sensibility should not, if possible, be dulled by gas-lights. It is well to have a gas-light over or near the lecture-table ; but its direct rays should be entirely kept away by a shade from both the spectators and the screen. One of the so-called self-lighting burners, which turn down the gas-flame to a small blue jet down in a metal cup, is very convenient. It cannot be turned out, yet leaves the whole room in darkness, and can be instantly turned full on. But in really delicate experiments, the direct light from a lamp should *never* be allowed to reach the eyes which are to observe them. For similar reasons, any opening at the back of the lantern or elsewhere should be well shaded by a curtain of black velvet or cloth.

CHAPTER II

RAYS AND IMAGES.—REFLECTION

Rays of Light—Rays form Images—Inversion of Images—Shadows—Law of Intensity at various distances—Law of Reflection—Virtual and Multiple Images—The Doubled Angle of Reflection—Application of this in the Reflecting Mirror—Reflection from Concave and Convex Mirrors—Images produced by Concave Mirrors—Scattered Reflection—Light Invisible.

14. **Rays of Light.**—All objects that are visible to us, are so in virtue of "rays of light" (whatever these may prove to be) which proceed from every point in the luminous surface. That these rays are perfectly straight or rectilinear while traversing the same medium, observation convinces us. We can trace the straight path of a sunbeam in a dusty room; we know, or find by experiment, that light from a lamp can only be seen through three perforated cards arranged with an interval between them, if all three apertures are in a perfectly straight line; and we are conscious that if any opaque body be held in the straight line between our eye and a lamp, the light is effectually stopped. But the rest of the mechanism—the real *image-forming* power of these rays—is masked to the ordinary observer by the number of them. To see it clearly, we must isolate the rays which proceed from the object in certain directions.

15. **Images.**—We may do this by darkening a room and

only allowing light to enter through a very small hole in the shutter—the original *camera obscura*. Bringing a sheet of white cardboard near the aperture (Fig. 19), we see depicted upon it the landscape outside, and we thus learn experimentally that rays of light really proceed from all points of visible objects, and that these rays form images. This is equally the case whether the objects are self-luminous, like the sun or a lamp

FIG. 19.—Image formed by a small hole.

(with which class of bodies we more commonly associate the idea of this ray-sending property), or whether they only reflect to us light derived originally from other luminous sources. In all cases the *image* is formed on the retina or on a screen, by rays which proceed from the object to the site of the image.

This landscape image is faint, because the objects depicted are not very brilliant, and there are too few rays passing through the aperture to form a bright one. We can get a brighter image by collecting wider cones of rays from each point of the object, methods of doing which will speedily come before us; or the more brilliant light of the lantern will yield a better one. Remove all the lenses, including the condensers,[1] and cover the flange-nozzle with a piece of tinfoil or a cap of black card. In this prick a hole with a rather thick needle,[2] and an image of the radiant at once appears on the screen. Since each point of this image is defined by straight lines proceeding from the corresponding point of the radiant through the prick to the screen, it is obvious that if we prick another hole we must get another image. We go on pricking holes, an image appearing with each, till by degrees the opaque tinfoil or card is removed. As we do so the images of the radiant crowd on one another more and more; presently they touch; then they overlap; at last, when all the tinfoil is gone, the screen is covered with a white glare of light.

16. **Necessity for Isolating Phenomena.**—We now see how the image-producing power of the rays proceeding

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[1] A simple and striking experiment for the private student is to take off the top, and knock out the bottom of a coffee canister, and blacken it inside. Then punch a hole in the middle of its length, about one-sixteenth of an inch in diameter. Hold this over a naked candle in an otherwise dark room; and a good image of the candle-flame will be formed at six or eight inches' distance upon a white card or finely-ground glass.

[2] A needle-prick will give good images from a lime-cylinder. With lower illuminants, the prick will have to be made larger, and a sheet of card, or the portable screen, should be brought within a few feet of the lantern.

from any luminous object, is ordinarily masked by the mere multiplicity of such rays. We say the screen is "lighted," but we have found that this illumination really consists in its being covered over by an infinite number of images of the radiant in the lantern. We thus learn at the outset a lesson of the greatest importance, viz., that in many cases, to ascertain the true nature of the phenomena of Light, we must *isolate* the rays concerned in them. Unless we do so, such a number of images (or other phenomena under examination) may get mixed up, or partially superposed, that the real character may be lost in a general confused body of light due to them all.

17. **Inversion and Relative Size of Images.**—It is plain, also, why such images as we have been forming must be *inverted*. Let O, Fig. 20, represent the original object; then

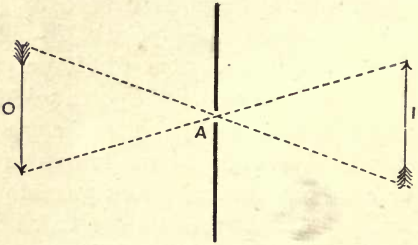

FIG. 20.—Inversion of Image.

it will be seen that the rays from its top and bottom, or right and left, if they proceed in straight lines, must cross at the aperture A, those from the top proceeding to form its image I at the bottom. It is further clear that the relative sizes of image and object must be exactly proportional to their respective distances from the aperture A. Both these truths are of general and important application in practical optics.

18. **Rays, Beams, and Pencils of Light.**—We have thus far spoken generally of "rays," but we soon perceive that a single ray must be in reality a mere ideal abstraction—

one precise mathematical direction, or line without thickness, out of many divergent rays from every luminous point. To get an image, as in Fig. 20, from single rays, the aperture A must be *infinitely* small; but under this condition visible phenomena would vanish altogether! In practice we can only deal with whole bundles of rays, the larger of which are usually called "beams," and smaller ones (whether parallel or conical) "pencils." If, however, we clearly understand this, it is convenient, in colloquial language, to speak of a small parallel pencil as a ray; and the word is often used, though not with strict correctness, in this sense.

19. **Shadows.**—That rays of light proceed in straight lines as long as they traverse the same medium, explains why opaque bodies cast *shadows*. Fig. 21 makes this clear. It is plain

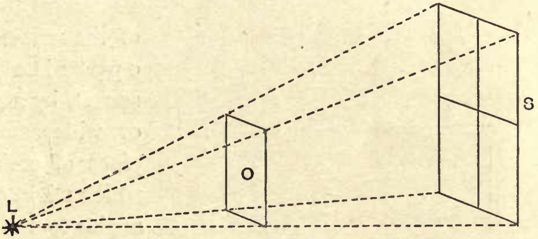

FIG. 21.—Shadows and Law of Squares.

that if the square of card (O) is held between a light L and the screen S, it must cast a shadow over the section of the whole cone of rays which it intercepts. It is plain, also, that while a small bright point of light must cast a sharp shadow, a large source of light must cast one fringed by more or less partial shadow called a penumbra; and if the source of light be larger than the intercepting object, at a certain distance behind the object there must occur a position where the whole of the light is never intercepted, and no total shadow exists.

20. **Law of Inverse Squares.**—Fig. 21 also illustrates the law of the *intensity* of light. If the object, O, is exactly half-way between L and S, its shadow will cover on the screen a space exactly equal to four similar squares. At twice the distance the light which reaches O has to cover four times the area; at thrice the distance, nine times. Hence the intensity of light is "inversely as the square of the distance" from the radiant point.

21. **Reflection.—Law of Equal Angles.**—We must now replace the condensers in the lantern and put on the optical objective, placing in the stage a blackened card or zinc plate 4 × 2¼ inches, with a horizontal slit in its centre an inch long and about ⅛-inch wide.[1] Three or four feet in front of the nozzle, N, place one of the pillar-stands, with the plane reflector, A B, in one of the horizontal sockets, as in Fig. 22. Fasten on the edge of the reflector just opposite to the socket, by a groove or wide saw-cut, a piece of cork, E, in which stick, at right angles to the reflector, a wire, C, as an index. The slit turned horizontally will project a thin slice of light (as it were) against the reflector, and it is at once seen that if this impinges at right angles it returns on its own path; but that, if the ray be incident at any angle with the perpendicular index, it is reflected at the same angle, as shown in the figure, on the other side of that perpendicular. A little smoke from a bit of

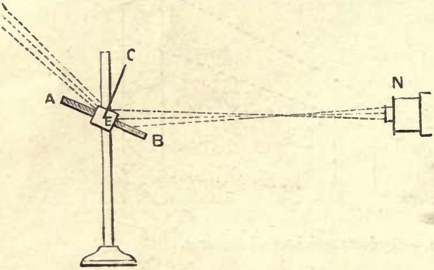

FIG. 22.—Reflection.

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[1] With the lime-light, if a nozzle with adjustable slit is at command, the parallel beam through this, without any objective, is better. See the note on p. 35.

lighted touch-paper[1] will make the course of the beam perfectly evident. Owing to the fact that any angle of the incident ray is thus reduplicated on the other side of the perpendicular, while the perpendicular incidence alone is reflected in the same path, this perpendicular is called the normal; and angles in optics are reckoned from the normal, and not from the actual reflecting surface. Thus the polarising angle of glass is called 56°, and not 34° which is the actual angle with the surface.

This fact, that the angle of incidence is equal to the angle of reflection, was about the first optical law known to the ancients, and has several important consequences. First of all, it leads us to a grand general principle of *reversibility*. That is, if the radiant were removed to the "other end" of the ray, the path traversed would be precisely the same, reversed. This is very generally true in practical optics.

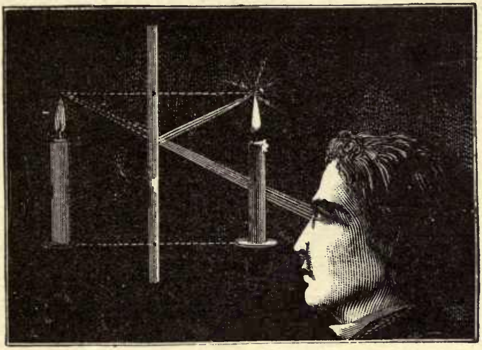

FIG. 23.—Reflected image.

22. **Virtual Images.**—Secondly, we perceive that a polished or perfect reflector must produce "virtual images." We "see" things in the direction from which the image-forming rays last come to the eye. Hence, taking the rays

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[1] Soft paper dipped in a solution of common nitre.

from a bright source of light, such, for instance, as a candle-flame (see Fig. 23), the divergent rays, when reflected, *appear* as though they proceeded from a point behind the mirror, at which therefore there appears a "virtual image."

23. **Multiple Images.**—As the eye can see the object direct, and also its virtual image, the object appears to be duplicated; and it is soon seen that if more than one mirror be employed, images may easily be further multiplied. Two parallel mirrors, by successive reflections, can be made to give a number of images; a familiar example of which may be found by looking at the image of a candle-flame in a piece of thick looking-glass held obliquely. A whole row of images will be seen, as in Fig. 24, owing to the rays being reflected and re-reflected between and from *both* surfaces of the glass. At a great angle of incidence, the reflection from the first surface of the glass is as bright, or even brighter than that from the silver surface; showing clearly that the comparative intensity or completeness of reflection from various substances, when polished, differs with the angle of incidence. If a piece of plain glass be used instead of looking-glass, we find also that reflection takes place, not only when rays encounter the polished surface of a denser medium, as glass; but also at the second surface, where the rays which have entered the glass meet the rarer medium of the air. We shall hereafter find that this last kind of reflection is often the most brilliant of the two.


FIG. 24.—Multiple images.

In all cases, reflection is the more copious the greater the angle of incidence, except in this last kind of reflection.

Repeated reflection sometimes produces most beautiful effects. When two mirrors are inclined together at an angle which is any aliquot part of a circle, or 360°, and the rays from any object pass between them so as to be reflected, there must be as many images (including the object) as the angle is contained in 360°. A glance at Fig. 25 will show how this occurs. Two such mirrors, or even plain rectangular oblong strips of plate glass, fixed in a tube, with a cap at one end made of two parallel transverse glasses, between which are loosely contained some coloured beads, or other transparent objects, and with a small hole in a cap at the other end of the tube, form the *kaleidoscope* of Sir David Brewster. In Darker's Lantern Kaleidoscope, the mirrors are of platinized glass, and are mounted with a convex lens at each end; thus mounted the apparatus takes the place of the ordinary lantern objective, and

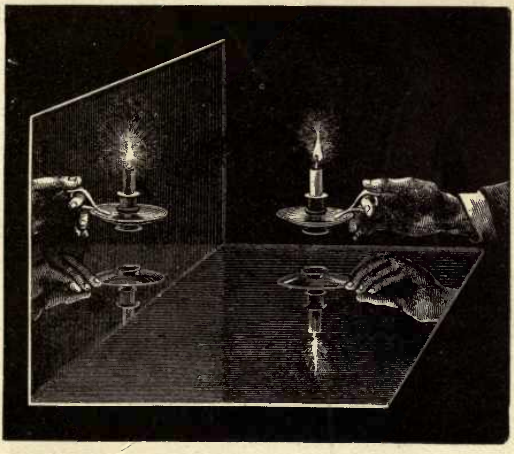

FIG. 25.—Symmetrical multiple images.

will produce beautiful patterns upon the screen if a rotating slide containing the fragments of coloured glass is placed in the ordinary slide-stage. In using this instrument the angle between the mirrors must be placed downwards, and the light must be *raised* half an inch to an inch above the usual central position, being adjusted carefully till all the segments are as equally illuminated as possible. The light which reaches the screen is reflected down upon, and upwards from, the mirrors ; and the effect will resemble that in Fig. 26. More perfect apparatus has been constructed in which the angle between the mirrors in the Lantern Kaleidoscope is adjustable by a screw, so as to divide the circle into different aliquot parts at pleasure.

Fig. 26.—Kaleidoscope.

24. **The Doubled Angle of Reflection.**—Another very important consequence follows from this law of equal angles.

It is obvious that in changing the position of the mirror, the reflecting surface itself moves through the same angular distance as the index or normal. Hence it follows that any angular movement of the mirror is *doubled* by the angular movement of the reflected ray; and this fact makes the "reflecting mirror" an invaluable method of demonstrating minute motions. We are familiar with the lever-index, moving from a centre; but in practice we are fettered in this means of multiplying a small motion, by the weight and other mechanical imperfections of an index-pointer of great length. In the reflected ray of light we not only double the angle to start with, but we have a pointer we can make of any length, which is absolutely straight, but which weighs nothing at all. Hence the "reflecting mirror" has constant applications, of which the following will serve as experimental examples.

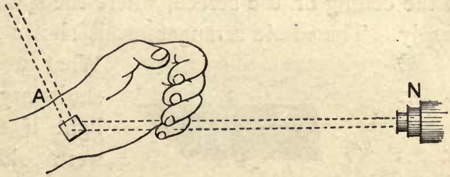

FIG. 27.

25. **The Reflecting Mirror.**—By keen sight, in the right light, the motion of the pulse may just be discerned, though it is almost imperceptible. But cut a piece of looking-glass an inch square, and paste on its face a bit of black paper with a circular hole ½ inch in diameter.[1] To the back attach in a triangle three pellets of wax, or anything that will stick to the skin, and stick the little mirror on the wrist, with one of the pellets just on the pulse. In the slide-stage place a zinc-plate or card with a ¼ inch circular hole, and focus the reflected

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[1] Still better for such experiments as these are silvered pieces of micro-cover glass, which can now be procured of many opticians.

image of the aperture. Hold the wrist in the beam, so that the incidence is about 45°, as in Fig. 27. At once the motion of the pulse is made visible to all by a motion of the reflected spot of light on the ceiling amounting to several inches. This is a very pretty and striking experiment, though simple. In preparing for it, it is well to find the exact spot on the wrist at leisure, and to mark it by a dot of ink.

In the same way we may demonstrate the rapid and minute motions produced by heat. Upon the table we adjust a Trevelyan rocker, A, with its block of lead, L, and fulcrum-knob as usual. Having heated it, we fix on its face, by any cement that will bear the heat, a small mirror B, like that just used, and by our glass reflector, C, direct the beam of light from a small aperture down upon it at any angle, so as to be reflected to the ceiling or the screen, where the spot should be focused sharply. The whole arrangement is shown in Fig. 28. What would be a stationary spot of light if the rocker were cold, is by the small rocking motion at once prolonged (by the persistence of impressions on the retina) into a bright line of light, and by gradually raising with the hand the block D bearing the fulcrum end, this is converted into a beautiful wavy line E F, which makes every separate motion visible. The rocker should be judiciously chosen by experiment as to its period of vibration.

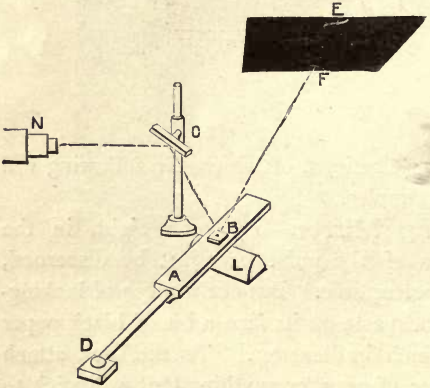

FIG. 28.

The elegant experiment of M. Lissajous may easily be illustrated with the lantern and such a tuning-fork as may be bought for 5*s.* On the outside of the end of one prong must be strongly cemented a small bit of silvered glass, and on the other a bit of metal or glass to balance it. We then mount the fork in a heavy block of lead, place a slide with a small hole in the slide-stage, and arrange the whole with the plane reflector in the vertical socket, as in Fig. 29, so that the light from the lantern may be reflected back from the mirror on the fork A to that on the pillar-stand B, and thence to the screen, where it produces a spot, which must be focused.[1] The card screen should also be placed between the fork and screen, with its blackened side towards the lantern, so that none of the incident beam may pass and interfere with the effect. On now exciting the fork by a violin bow, the spot is expanded by the angular

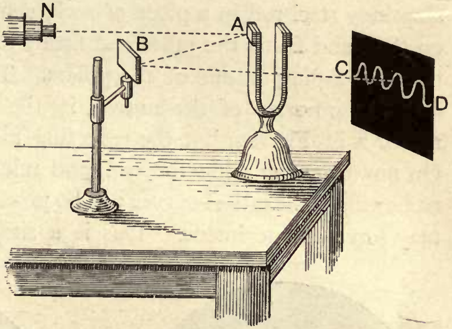

FIG 29.

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[1] *Note on Parallel Beams and Pencils.*—It may be well to allude briefly to various methods of producing parallel beams and pencils. For merely *parallel* beams, the radiant is pushed up into the principal focus of the condensers, so as to make the whole beam parallel, and an aperture of the required size and shape is placed on the open end of the nozzle. With a gas-burner this will however scatter considerably, but may be sharpened by inserting in the ordinary slide-stage, or anywhere some inches farther back, a similar aperture rather larger. Such merely parallel beams are sufficient for such experiments as those in refraction, Fig. 39, 42, 43. But it is an improvement even with such experiments to *focus* the aperture, either with the loose lens, or by the optical front with the aperture in its stage; and for figures described by a bright spot on the screen this is essential. The beam should however not be focussed anyhow, but *first parallelised* as far as possible. For circular pencils the attachment shown in Fig. 2 is of great service, increasing the brilliance materially.

motion of its mirror into a bright vertical line; and by slightly turning the reflector B in its vertical socket, this is developed, as before, into a beautiful undulatory form C D, showing each vibration of the fork. We may, as is well known, substitute a second fork fixed horizontally for the mirror B, and thus get beautiful compounded curves; but this belongs rather to another subject, and a pair of really accurate forks are expensive. The *optical* effects may be simply obtained by fixing the end of a springy steel rod in a piece of cork, cementing a small mirror on that, and fixing the other end firmly by a screw into a mass of metal sliding on one of the pillars. This is presented "end on" to the nozzle of the lantern, in the position of the fork-mirror A in Fig. 29, but the reflecting mirror B is not moved. On now drawing aside the rod, and releasing it, or striking it, or bowing it, beautiful curves will be produced, of which Fig. 30 may serve as specimens. This is a simple screen adaptation

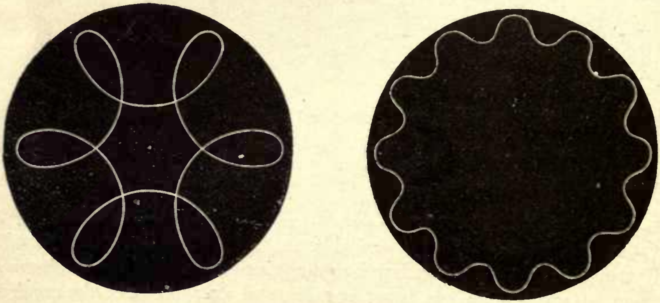

FIG. 30.—The Kaleidophone.

of Sir Charles Wheatstone's *Kaleidophone*. Mr. Ladd invented a modification, in which the rod is made of two steel slips of different lengths joined together so as to give transverse sections; when, by bringing more or less out of a screw socket, almost any of Lissajous' combinations can be produced.[1]

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[1] Forks that perform very well optically, may be bent up of steel about 1 × ¼ inch. The arms should be about a foot long, and each arm furnished

Get a large and thin claret or champagne glass—the larger the better—say 3 inches diameter, and fill to the brim with alum-water. Adjust this on the table as in Fig. 31, the reflector A throwing the full light from the nozzle N at a slight angle down on the glass, and the lens B focusing the surface on the ceiling.[1] On now ringing the glass by the edge of a knife, circular waves of light and shade will be seen: and on dipping the finger in the alum-water and—holding the stem firmly down—rubbing the edge till the well-known sound is produced, small ripples will cover the surface in exquisite patterns, and follow the finger round, all being reproduced above on the ceiling. A violin-bow, besides being in the way, produces somewhat too strong vibrations.

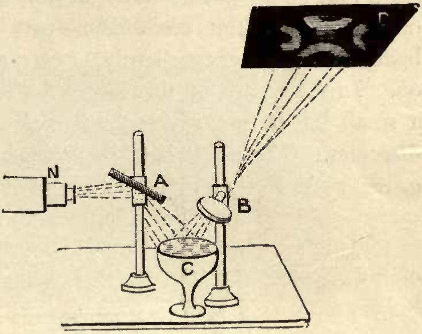

FIG. 31.

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with a metal socket sliding easily on it, and fixed by a screw at any point. By these movable sockets we have much control over the periods of vibration. Such forks need not be polished. By far the most effective apparatus for projecting Lissajous' figures is one of *reeds* mounted with mirrors, which I have described elsewhere, and which can be procured with a complete octave of notes for about seven guineas. It will also project beats and other scroll figures.

[1] If an Argand burner is used, we want all the light, and the reflector and glass must be so brought up near the nozzle, that all is collected just into the circumference of the water. All scattered light must also be carefully stopped; seeing no light escapes anywhere, and standing the glass itself on a piece of black cloth, that no light may be reflected from the table surface to the ceiling. In working with a low illumination much depends on these precautions, and with them this beautiful experiment will show very fairly on a ceiling 9 or 10 feet high; a reflector in the lantern is also of service. With the lime-light we need not be so particular, or the glass may be placed in the phoneidoscope described in § 108.

The vibrations due to sound may be shown by the reflecting mirror in yet another way, due originally to Professor Dolbear. Procure a tube of any material about 1½ inches diameter, and say a foot long—paste-board will do, or metal. Over one end of it stretch any thin membrane—part of a child's india-rubber balloon will answer excellently, or even a piece of paper gummed on. In the centre of this fix by a little gum or other cement a small bit of thin silvered micro-glass, not exceeding ½ inch diameter. The whole is to be arranged in any kind of crutch or rest as in Fig. 32, reflecting a spot of light to the screen from the small mirror and plane reflector. Then sing into the open end of the tube. Every note will produce a line or figure of some kind, the figures often taking symmetrical forms, as the membrane vibrates under the sonorous vibrations in the tube. This simple experiment is very interesting and beautiful. Still more beautiful methods of optically representing these sound-waves will come before us when we consider the colours of thin films. Meantime these experiments may suffice for the power of the reflecting mirror; which finds its fullest development in the "rotating" cubical mirror of Sir Charles Wheatstone, by which the velocity of light itself was measured by Foucault with such marvellous accuracy.

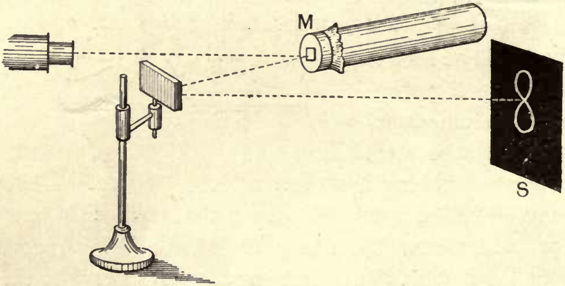

FIG. 32.

26. **Reflection from Curved Surfaces. Concave Mirrors.**—Further consequences follow from the law, or fact,

that the angles of incidence and reflection are equal. Let us suppose our reflecting surface, instead of being flat, is curved, as in a portion of a sphere, of which a section is shown in Fig. 33, the centre of the curve or sphere being at C. A drawing upon a large scale will speedily show that a series of parallel lines, representing rays, leaving the mirror A at equal angles to those of incidence, must meet or converge *nearly* at the point F, midway between C and A. If we take a divergent pencil as in Fig. 34, we find still the same thing: here C is the centre of the mirror, from which all lines drawn to it are perpendiculars to its surface. One such normal is shown by the dotted line, and simple inspection makes it evident that the

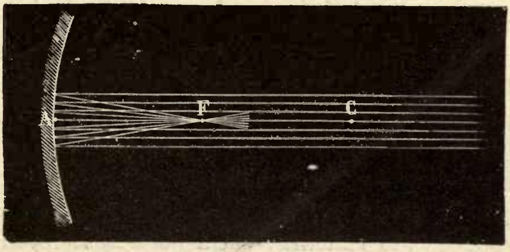

FIG. 33.—Concave Mirror.

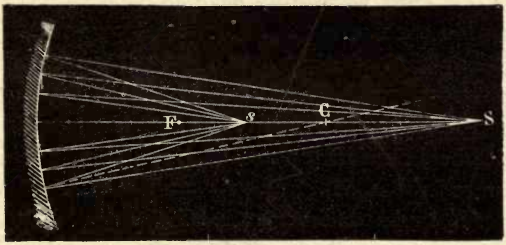

FIG. 34.—Image formed by Concave Mirror.

lowest ray from S, reflected from the mirror at an equal angle on the other side of that dotted line, proceeds to *s*, and that every other ray from S is reflected to nearly the same point. The qualification "nearly" is necessary, because mathematical analysis proves that only a parabolic form will *exactly* converge parallel rays to one point, and that a spherical mirror only exactly converges rays emanating from the centre of the sphere. But for small surfaces the aberration is not great even with spherical mirrors; and these are the correct figure for aiding the light in lanterns or electric cameras, the rays proceeding from the centre of curvature, and being reflected back through the same point, so as to reach the condensers at exactly the same angles as the direct light. Parabolic mirrors are often fitted by opticians to lanterns; but a moment's reflection will show that such an arrangement is a mistake, as the condensers cannot deal properly at once with the divergent light from the radiant, and the parallel light from the mirror. On the other hand, when a strong parallel beam is required, as in lighthouses, the parabola is the correct form. The point where parallel rays converge is called the principal focus.

27. **Images from Concave Mirrors.**—As the rays from one point are collected by a concave mirror to another point, as in Fig. 34, we must necessarily have an image (§ 15). And because a wide cone of rays is thus collected and converged, this will be a *brighter* image than those previously obtained. We have supposed S to be a point in Fig. 34, but if we take an object A B (Fig. 35) and trace only two diverging pencils for the sake of clearness from its top and bottom points, we shall see that both rays from A converge to *a*, and both from B at the point *b*; parallel rays crossing at F, the principal focus of the mirror, and rays perpendicular to the surface at C, the centre of curvature. If *a b* is the object, then the enlarged image will appear at A B, owing to the principle of reversibility (§ 21). Inspection will show that the image must be inverted.

All this can be easily proved by experiment, a concave silvered glass mirror 6 or 8 inches diameter being now procurable for a few shillings, and answering the purpose sufficiently,[1] the secondary image from the first surface of the glass being too faint to matter much in mere demonstration. We simply remove the objective from the lantern, deflect it about 90° from the screen, and place in the ordinary lantern slide-stage any diagram, or some simple lantern-slide. The concave mirror (of not less than 6 inches focus) can then easily be so held by hand as to throw a recognisable image of the slide in the lantern upon the screen.

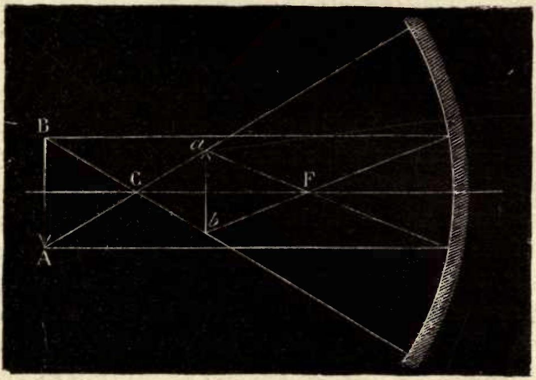

Fig. 35.—Inverted Image.

This, then, is one method of collecting sufficient rays from an object to form bright images; which is practically utilised in the *reflecting telescope*, largely used for astronomical purposes. The rays to be collected being practically parallel, the figure of the mirror is parabolic; and the collected rays may be brought to the eye in either of several methods, which need not be

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[1] For private experiment the phenomena of curved mirrors may be easily traced out by blacking the convex side of a watch-glass for the concave mirror, and the concave side of another for the convex mirror.

described in a work dealing only with the physical phenomena of light.[1] If the pupil of the eye be, say $\frac{1}{8}$th of an inch in diameter, and we "see" a star by the "light" which enters that small area, it will readily be understood how many thousand times the same quantity of light will be collected by a good speculum several feet in diameter, and how much magnification an image so produced will bear, without too much loss of brilliancy.

28. **Convex Mirrors. Virtual Images.**—The images just considered are *real* images: that is, the rays diverging from all points of the object being actually converged to certain points, if a screen be adjusted at these points the image or picture will appear upon it. A few moments' consideration and a simple diagram [2] will show that if an object be placed in front of a convex mirror, the divergent rays from it must be reflected still more divergent, and must, therefore, since the rays are "seen" in their last apparent direction, *appear* to proceed from a point behind the mirror, obtained by prolonging behind it the reflected ray-lines. Such an image appears smaller, and erect, and is a "virtual" image, having no real existence. If an object be placed nearer a concave mirror than its principal focus, a diagram will also show that no real image can be formed, but that a "virtual," erect, enlarged image will appear behind the mirror.

29. **Scattered Reflection.** — Turn the lantern again towards the screen, throwing from it either a beam of parallel light, or the image of an aperture an inch diameter if a plain burner is employed, stopping the beam with the black card screen at the end of the table. With the plane mirror throw the beam back, and rather towards the ceiling, to any point not

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[1] These and other optical instruments are fully explained and illustrated in Guillemin's *Applications of Physical Forces*, published by Macmillan and Co.

[2] The student is strongly advised to construct such diagrams *for himself*, solely by the method of drawing ray-lines at equal angles of incidence and reflection.

very white or light-coloured. Nearly the whole of the light will be reflected, but the mirror itself will be little illuminated, and the room itself will remain nearly dark. Now take the card screen, and turning round its *white* side, use that in place of the mirror. The beam of light is no longer reflected as before (in the form of a bright beam) to the ceiling; but the card is brightly illuminated, and a very considerable amount of light is diffused throughout the room. Hence the light appears at first sight to be reflected according to different laws in the two cases.

But it is not really so; and this simple experiment, with what we have already discovered about forming images by collecting and converging diverging cones of rays, explains to us how *things* become visible, or send light to us, though that light be only borrowed or reflected. We can understand in a moment that a *perfectly* polished surface, if such were possible, can only reflect to us or converge for us, the diverging rays from other and luminous objects, without altering them otherwise. It must itself, therefore, be utterly invisible! Such a perfect polish is unattainable, but our nearest approaches to it prove the truth of this. It is not uncommon for a large mirror occupying the whole of one end of an apartment, or the side of a landing, to be unperceived;[1] and Colonel Stodare's "Sphinx," which made some sensation years ago, depended upon the space between the legs of an apparently three-legged table being glazed with brilliant looking-glass. The stage being kept in a rather subdued light, and the carpet and hangings carefully arranged of uniform colour, with no "pattern," to all appearance there were only three legs under the table and box which supported a living head; whereas the man's body was comfortably accommodated behind the two silvered mirrors, placed with their angle of junction towards the spectator.

With surfaces not perfectly polished, or—which means the

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[1] I once actually walked up against a large mirror placed at the corner of a club staircase, and occupying the entire wall at the corner.

same thing—not perfectly *smooth*, it is very different. Let Fig. 36 represent such a surface, with its inequalities highly magnified. The rays from the left hand, say of a sun-beam, strike upon it all parallel. But even the few which for the sake of clearness are drawn, are reflected in all directions, owing to the furrows and protuberances of all sorts, which make the angle of incidence variable for almost every one. It can be seen that every reflected line in the diagram is drawn at the proper angle; yet how different these reflected directions are! In reality the variety of directions is countless; and thus from every sensible portion of the surface comes, not the original parallel pencil of rays, but a *cone of divergent rays.* The body itself thus behaves like a candle, or has become luminous, though only by reflected light; and so it is that if we collect and converge these new cones of rays, either by the eye, or by any other methods, we form an image.

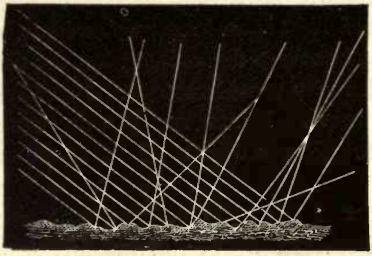

FIG. 36.—Reflection from Unpolished Surfaces.

30. **Light Invisible.**—We push our experiments on scattered reflection a step further, for it bears upon a very important matter. Already we cannot help asking ourselves, what *is* this Light, which obeys rigidly such simple laws, and yet produces such various effects by them? The equal angles of reflection and incidence almost irresistibly suggest to us a ball rebounding from a wall, or a billiard-ball from a cushion. It is natural to conceive of Light as consisting of infinitely small and highly elastic particles, propelled from the original luminous source. Such a hypothesis would account for most of what we have found, if not all, and is very simple, and easily

understood. But besides far greater difficulties we must grapple with later on, this hypothesis has one obvious difficulty that encounters us even now. Light ought, if it were so, to be *visible*. And indeed we are apt to picture it as possessing intrinsic brilliance of its own; and we have even appeared in many of the previous experiments to "see" the course of the rays—the very "rays" themselves—in our darkened room.

Nevertheless it is not so, as a careful consideration of our last experiment soon leads us to perceive. This Light we are studying is not itself a Thing, but a Revealer of things. It is itself, and by itself, absolutely *invisible*. It *makes* visible to us, luminous objects or sources, rays from which actually reach our eyes; but if we look "sideways" at rays alone from the most dazzling light, we cannot see them. Space is black. If we appear in previous experiments to have "seen" the course of the rays in our darkened room, that is only because of the little motes in the air; and Professor Tyndall has shown that, destroying these by heat, and keeping fresh intruders out of a glass tube thus cleared, the space traversed by the full beam of an electric lamp is dark as night. We demonstrate it less perfectly, but sufficiently, as in Fig. 37. Place on the table a confectioner's glass jar, A, 6 inches in diameter, cover it with a glass plate, B, and drop into it a bit of smoking touch-paper, which soon fills the jar with smoke. Adjust the plane reflector, C, to throw the whole beam down as parallel as possible, when the jar is at once filled with a peculiar lambent light. Take off the plate and let the smoke out; and, as it disappears, dark spaces appear where there are no particles to reflect the light, till all is dark. The Light itself is there alike at all times; but where there are no solid particles to reflect it actually *to the eye*, we see nothing at all. The Light that illuminated the jar, is itself invisible.

Once more: clear the jar and fill it with clean water. Again it is almost invisible, except where the rays may be reflected from some point of the glass direct to the eye; and it would be quite invisible were the clearness of the water and polish of the glass perfect, as we have seen (§ 29). But now pour in one or two spoonfuls of milk and stir it up. At once a splendid opal light fills the jar, and a pleasant radiance the room.

Many students, and even teachers, too much despise these more simple experiments; but they are not only of great beauty, they are pregnant with meaning. We have here not only a difficulty in the "emission" theory which we must not

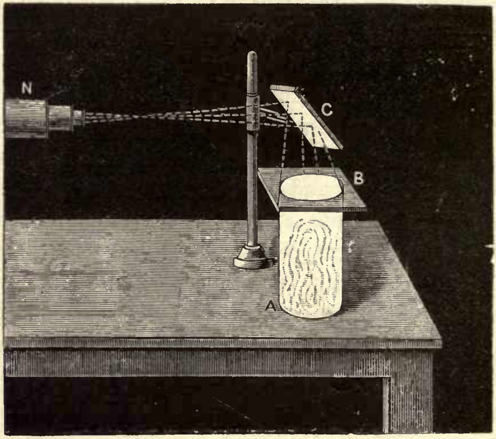

FIG. 37.—Scattered Reflection.

forget, but we have had another striking example of scattered reflection—that kind of reflection by which bodies are seen. In white light, more or less of such scattered light is always white. Therefore "coloured" bodies reflect white light as well as coloured; and more white light will be reflected from a black hat in the light, than from a shirt-front in the shade. Smoke is soot, and we all know soot is black; but in our last experiment but one, the light we got reflected from our particles of smoke, when diffused, was white.

CHAPTER III

REFRACTION.—TOTAL REFLECTION.—PRISMS AND LENSES.

The Refraction or Bending of Rays—The Law of Sines—Index of Refraction—Total Reflection—The Luminous Cascade—Transparency—Prisms—Lenses—Images produced by Lenses—Focus of a Lens—Virtual Images and Foci.

31. **Refraction.**—Provide a rectangular tank about two inches between the sides, one of which, to serve as the front, is a piece of glass a foot square, or a little more; let one end also be of glass, and the top open. Paint over the face with black varnish all but a circle, on which paint a horizontal and vertical diameter, as in Fig 38. Provide also a strip of thin zinc or copper blackened, C D, rather wider than the tank, and about three inches longer, in which cut two slits $\frac{1}{8}$ inch wide, and nearly the whole width of the strip (or depth from front to back of the tank) in length, in such positions that when the strip rests vertically against the glass end, the slit E shall be about $\frac{1}{2}$ inch above the horizontal line, and the slit F make an angle of 40 degrees from the centre of the circle with the horizontal line.

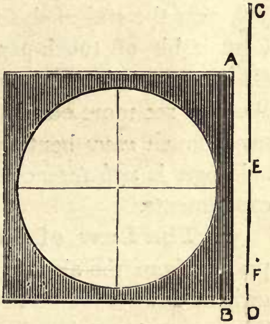

FIG. 38.

Fill the tank exactly to the horizontal line with water mixed with two or three drops only of milk, or a grain of eosin, uranine, or any other fluorescent substance; place the metal strip over the top with both slits towards the lantern, and arrange the reflector as in Fig. 39, placing in the optical stage the slit used in our first experiment in reflection, horizontally, or using the parallel beam. First of all direct the light through the slit E (Fig. 38), only a little off the vertical, covering over the other slit. It will be seen that the ray is bent or refracted on entering the water. Cover up this slit and uncover the slit F (Fig. 39), near the end of the tank, and blow in a very little smoke from a bit of touch-paper to show the course of the ray. (If too much is used the light will be scattered, as in § 30.) We now see more clearly all that takes place. First of all, the ray is much *more* bent than before; and secondly, a considerable part is *reflected* according to the law found in our former experiments.

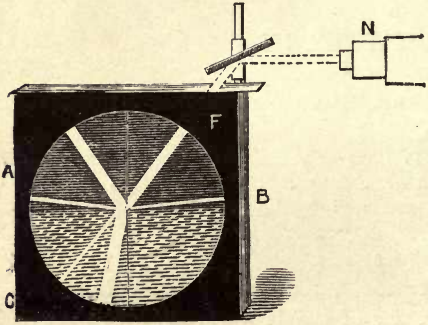

FIG. 39.—Refraction and Reflection.

32. **The Law of Refraction.**—We have found that in passing from the air into the water the ray of light is wrenched or bent down towards the vertical, or *refracted*, as it is called. The greater the original angle with the vertical, the greater also is this bending; and we naturally inquire if there is any law which governs these variable angles of deflection. The law is simple enough when known, but not very obvious to mere observation. It eluded even Kepler's special investigation, and was only discovered about 1620-25, by Willebrod Snell. It is

called the "law of sines." Taking a circle, as drawn on the face of our tank, described round the point where the ray enters the denser or more refractive[1] medium, and drawing the perpendicular or normal, A B (Fig. 40), which in the case of water is of course vertical, we may take any incident ray, D C, and its refracted ray, C *d*. From the points at which these cut our circle we let fall D S and *d s* perpendicularly upon the normal A B. Then D S is the "sine" of the arc subtending the angle of incidence, and *d s* that subtending the angle of refraction, and the two lines will have a certain proportion; in the case of air and water here supposed, it is almost precisely as 4 : 3. Now take any other angle of incidence, E C, and its refracted ray, C *e*, and drawing the sines as before, they will have *precisely the same proportion.* All the sines have the same invariable ratio.

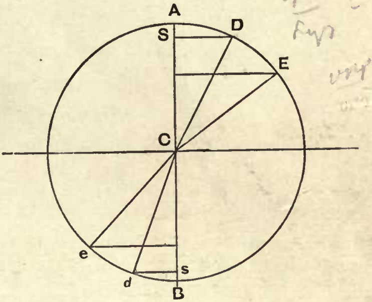

FIG. 40.—The Law of Sines.

33. **Index of Refraction.**—When this proportion of the sines is put into the form of a fraction—generally a decimal fraction—it is called the "index of refraction." Unless otherwise specified, figures so given are understood with reference to *air* as unity. In the case of air and water we have seen that this ratio is *nearly* $\frac{4}{3}$; and when put into decimals, 1·335 is the "index of refraction" for water. It follows, that the greater the refractive power the higher the index must be.

34. **Refraction into a Rarer Medium.**—We have

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[1] A heavier fluid may have less refractive power, or *optical* density, than a lighter one. Oil of turpentine floats on water, but has much more refractive power.

proved that a ray passing obliquely from air into water is bent towards the vertical, or downwards; and yet if we look at a stick standing in clear water it *appears* to be bent upwards. Fig. 41 explains this. The dotted lines represent the real position of the bottom part of the stick, and those dotted from its lowest point show the course of the rays which reach the eye from that point. On reaching the surface they are bent *from* the vertical, and the bottom of the stick is "seen" in the direction from which the rays actually enter the eye. We thus see that the course of the refracted ray, like that of a reflected ray, is exactly *reversible.* If the bottom of our tank is made of glass, and it is raised up from the table and a ray sent *up* through the water, it can be shown experimentally that at sufficient angles the ray is refracted from the vertical on leaving the water: or the ray may enter the top of the tank as before, and after first being refracted downwards, will, on passing through the glass bottom, be again refracted away from the normal.

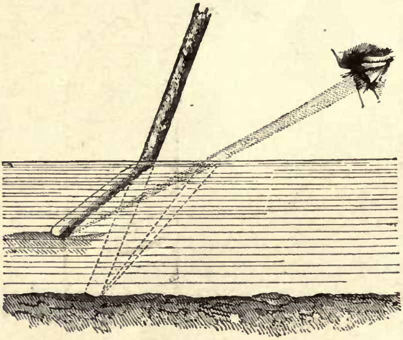

FIG. 41.

35. **Total Reflection.**—But there is a curious limit to this. Seeing that as the angle of incidence increases, the refracted ray is more and more bent towards the vertical, we cover the top of the tank with a bit of plain board, and place the metal strip upright against the end of the tank, in the position of Fig. 42. Gently canting our lantern a little, we pass the beam direct through the slit E (Fig. 42), so as to enter the water almost horizontally. We find the ray bent down

a great deal, at about an angle of 45°, as shown by the thin white line C D. Now we have ascertained that if we throw the ray first by our reflector *up* through the water, in this case the path is exactly *reversed.* It occurs to us at once, that if we sent our beam at a slightly greater angle (never forget that all angles measure from the normal) through the water, there is no path in the air it can assume: it would appear that it cannot get out of the water at all. We try it, as in Fig. 43, sending our beam up through the lower slit by a bit of looking-glass, so as to strike the centre at an angle of 50° from the normal.[1] It does *not* get out—not a sign of it. It is totally reflected; and because this reflection is total, it has a brilliance not possessed by that from even the best silvered mirrors. It will be readily seen that the angle of total reflection must *decrease*[2] as the index of refraction *increases;* but this will be shown by a beautiful experiment when we come to study the subject of colour (§ 47).

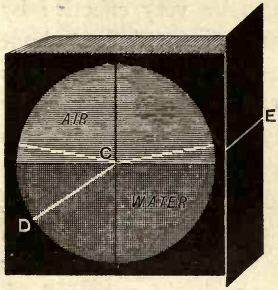

FIG. 42.

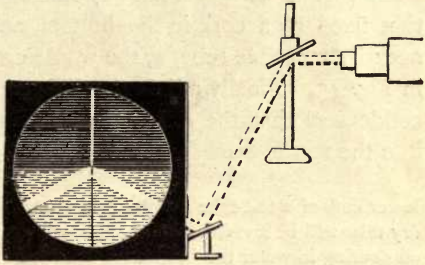

FIG. 43.—Total Reflection.

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[1] The limiting angle is about 48°, but we keep on the safe side.

[2] The phenomena of total reflection may be observed by the private student by looking at the under-surface of the water in a tumbler held rather above the level of the head and of a candle, or by immersing the

36. **A Luminous Cascade.**—There is another very beautiful method in which total reflection may be illustrated by the lantern, called the "luminous cascade," or "fountain of fire," which may be arranged so as to be very effective by simple means. Get a two-necked glass receiver (Fig. 44) about 4½ inches diameter, with as large necks as possible, and in each neck fix by corks glass tubes of similar size, as large as possible, not less than ⅜ inch clear bore, and ½ inch is better.[1] Black-varnish all outside, except a circle, C, three inches diameter, opposite the neck meant to be horizontal; and adjust this as at A (Fig. 45) close against and projecting into the lantern nozzle (the flange nozzle, with the objective removed), on any stand, filling with water first, and corking the tube in the horizontal neck till all is arranged. Several feet higher, fix some sort of supply tank (a bucket will do) with a bit of tube fixed by a cork in the bottom, and connect with the top neck by a flexible tube, B, the whole arrangement being shown in Fig. 45. Finally adjust the light at such distance from the condensers that the greatest possible amount is concentrated into the space occupied by the emission-nozzle. Having ad-

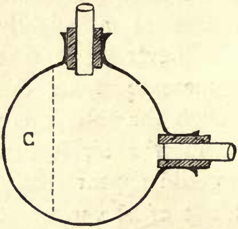

FIG. 44.

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lower end of a test-tube slantwise in water. Whatever is placed in the dry tube will be invisible, and the tube will appear brighter than silver; but on pouring in water the brightness disappears and the contents of the tube become visible.

[1] There is sometimes difficulty in procuring a receiver with both necks large enough, on a small globe. In that case, insert as large a tube as it will take in the largest neck, for the emission opening, and strain the flexible supply tube over the other neck alone, which will give plenty of aperture for the supply. A fair-sized stream must be obtained; otherwise there is not enough light, and it breaks up too soon into drops. Since this work was published, several opticians supply at my suggestion a cheap metal closed tank with a flat glass side and an opposite nozzle, on purpose or the experiment.

justed all this, and filled the tank, remove the cork from the tube, and let the water stream out in a gentle curve into a bucket on the floor. The effect is beautiful even on this small scale. The jet is like a stream of living fire; and if we have some coloured glasses and slip them in turn into the ordinary slide-stage of the lantern, we get blood-red, blue, or what colour we desire. All this is owing to "total reflection." If the water did not issue, and we replaced the cork by a ground-glass stopper with flat polished ends, we know the light from the lantern would be thrown horizontally into the room. But it meets the stream of water on every side at much more than the angle of total reflection; and so it cannot get out, but is reflected from side to side all down the stream, making it brilliantly luminous by the small motes in the water. Place the hand in the jet, and it is bathed in light—that light

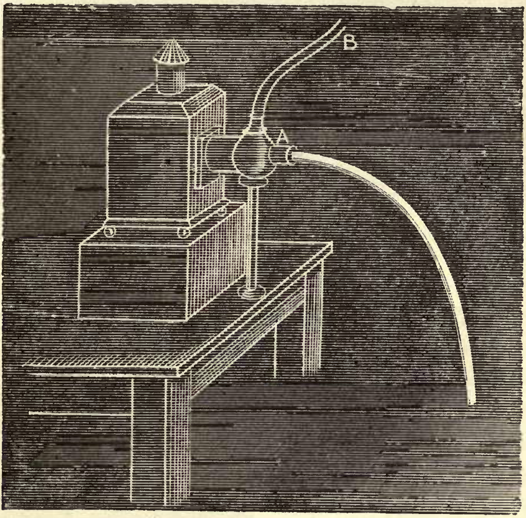

FIG. 45.—Luminous Cascade.

which cannot get out of the stream except where we thus break it up.

37. **Deflected Rays.**—We must, however, follow refraction a little farther. We have seen that the path of a refracted ray is reversible, and that, on leaving the denser medium, it is bent *from* the perpendicular. We easily see (Fig. 46) that if a ray, s, passes from and into air through a denser medium with parallel surfaces, as a thick piece of plate glass, it must be deflected somewhat, but finally resume a direction *parallel* to the original, as if proceeding from s¹. We may demonstrate this with the lantern, by placing in the ordinary stage with objective removed, and focusing on the screen with the loose lens, a blackened glass slide with one or more perpendicular lines, or other figures, scratched in white through the varnish. Now hold across the slide a strip of plate glass $\frac{1}{4}$ inch thick, so as only to cover a portion of the figure. When this is held parallel to the slide, there is of course no perceptible refraction; but when the plate glass is held obliquely, so that one end is farther from the slide than the other, the lines as far as covered are perceptibly deflected or broken. (Fig. 47.)

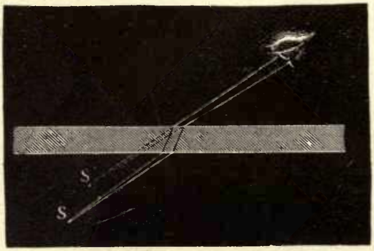

Fig. 46.—Deflection.

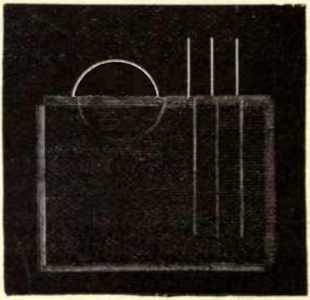

Fig. 47.—Deflected Image.

38. **Transparency.**—It appears very readily that the pro-

perty of transparency must depend upon homogeneous structure and uniformity of refractive index, and is reciprocal with irregular reflections and refractions. Arrange a screen of blotting paper between *two* lanterns if available, or if not between two gas-burners, so that it may be visible by reflected light from one source, or by transmitted light from the other. Oil or damp a small portion in the middle. By the oil or water the difference in refractive index between the fibres of the paper and the intervening pores is largely diminished, water or oil being denser than air; and this portion will therefore appear darker by reflected light, but *brighter* by the transmitted light. If thin ordinary paper with a grease spot be used, with the lantern on one side and a burner on the other, altering the distances till the paper appears equally bright all over, we have in a rough form *Bunsen's photometer*.

But we can demonstrate the same thing by a far more beautiful experiment. Provide a bottle cemented like a prism-bottle, but with two parallel sides of plate glass about half an inch apart; or even one of the cheap scent-bottles ground to two flat sides will answer less perfectly. Prepare also some pounded glass, from any fairly homogeneous piece in the first case, but for a common scent-bottle one or two *similar bottles* should be pounded up, heating the glass and throwing it into water. Common powdered glass, as sold, rarely answers, being usually a mixture of all sorts, and not of the same index. The bottle is filled with this, and the irregular refractions and reflections of the particles are so great, that the mass is perfectly opaque. By mixing in proper proportion benzol (less dense than glass) and carbon bisulphide (more dense) prepare a fluid of the same refractive density as the pounded glass, and pour it in. The fluid is easily mixed by "trial and error," in a bottle containing a few fragments of the glass. The bottle is now transparent, and will allow the rays of the lantern to reach the screen. A further refinement of this instructive experiment will occur later on (§ 60).

39. **Prisms.**—If the two surfaces of a piece of glass through which a ray of light is sent are inclined to each other, the ray must be permanently deflected into a new direction. Any refracting body with faces so inclined is called a prism. Fig. 48 shows a section of such a prism, and it is clear that a ray, S I, impinging on the first surface at the angle S I N with the normal N, will be refracted in the path I E towards the perpendicular. But E N′ is the normal to the second surface, and on emerging the ray must be refracted *from* that, in the direction E R, widely different from that of the incident ray. It is equally clear that the deviation must depend not only on the density, but on the angle of the refracting surfaces of the prism. It also, however, depends on the *position* of the prism (§ 40).

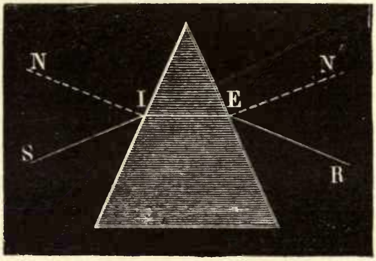

FIG. 48.—Prism.

All this is easily demonstrated; but to avoid much colour phenomena, which must be studied separately, it is best to take a water-prism of rather a small angle; or if of glass a very thin one indeed, usually called a wedge-prism, costing about 3*s.* 6*d.* A water-prism is readily constructed by shaping a smooth wedge of beech about 3 inches square, one inch thick at one side, and tapering to an edge at the other. Bore centrally through, from face to face, a circular hole 2 inches diameter; paint the inside of the hole with sealing-wax varnish; and then, heating two clean pieces of plate glass 3 inches square, cement them with hot sealing-wax or shellac on the flat sides. By a small hole bored from one end of the wedge this prism may be filled with water, or the hole may be entirely opened out to one end so as to form a small open trough. Placing a small aperture in the optical stage, and focusing on the screen, stand the water-prism on one end on the table-stand (Fig. 11) and adjust in the path of the rays. It will at once be seen how the image is deflected. If a multiplying glass, which can be bought for a shilling, is held in front of the nozzle, a number of refracted images will appear on the screen.

40. Position of Minimum Deviation.—It will soon be found that the deflection varies as the prism is turned round upon its axis into different positions. It will also be found that the deflection or refraction is least when the prism is placed as in Fig. 48, so that the incident and refracted rays make *equal angles* with their respective surfaces. This position is known as that of "minimum deviation," and is carefully arranged for in all accurate prism work, such as spectrum analysis.

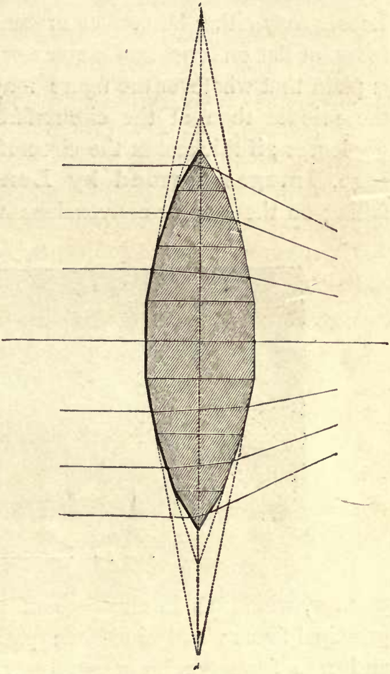

Fig. 49.—Nature of a Lens.

41. Lenses.—Let us now consider a number of prisms of gradually increasing angles, arranged round an axis. Fig. 49 may represent such a combination of prisms in section. A glance at the diagram shows that the outer parallel rays, from the left hand, meeting prisms at greater obliquities, are more deflected than those nearer the centre; and that if the obliquities are properly adjusted, all the rays might be made to converge in one point. If the obliquities are infinite in number, it is obvious that we get *curved* surfaces, and such form a *lens*. Lenses may either be convex or concave on either or both surfaces, or flat on one, and convex or concave on the other. It is plain that whatever the figure may be, if they are thicker in the middle than at the circumference they will be *converging* lenses; if thickest at the circumference, *diverging* lenses.[1]

42. **Images formed by Lenses.**—Since parallel rays, falling on the double-convex lens A (Fig. 50) converge to the point F, which (as in the case of a converging mirror) is the principal focus; and since the path of the rays is reversible, and rays from the point F after traversing the lens become parallel; a moment's consideration will make clear that if the rays diverge from any point *beyond* the principal focus, they must converge to some other point and form an image. Fig. 51 shows this. Parallel rays from A B traversing the lens O would converge at the principal focus F; but if rays *diverge* from the points A and B of an object (only pairs of rays are shown

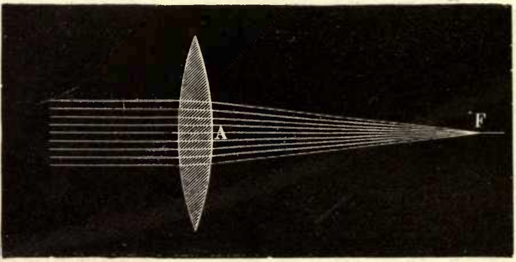

FIG. 50.—Lens and Focus.

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[1] A lens formed by two equal convex surfaces is called a double convex lens, and if the two convex surfaces are of different curves, a "crossed" lens; lenses with two concave surfaces are double-concave lenses; those with one side flat, plano-convex or plano-concave; a lens with one side convex and one concave, a meniscus.

for the sake of clearness) they converge to the points *a b* and form an image. It is also clear how the respective distances of image and object govern their respective sizes, so that if *a b* is the object, A B will be its image. Also that the image thus formed must be inverted. Thus we have a second method of forming brilliant images, the lens taking up a large cone of rays from each point of the object.

But it is very important to realize clearly that this image is formed by the *rays of light* proceeding from each point, precisely as in § 15, and that all the lens does is to converge (upon the same point in the image) large bundles of rays. Repeat the lantern experiment in § 15, removing all the lenses,

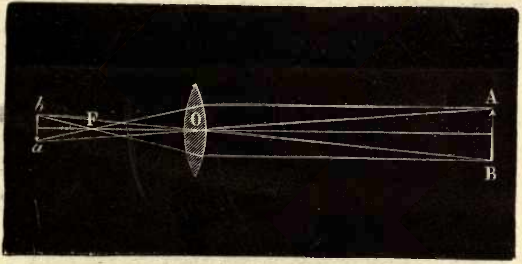

FIG. 51.—Image formed by Lens.

covering the flange-nozzle with foil, and pricking a hole in the middle, and say four other holes equally spaced half an inch outwards from it. We get from the bare rays alone, as in § 15, an image of the radiant in the centre of the screen, and four other images ranged round it, which represent diverging rays. Now take a large lens of somewhat longer focus than the distance of the radiant from the tinfoil, and hold it in the hand close to the foil. It will be instantly seen that the four outer images are bent in more or less towards the middle one ; and a position is soon found, in which they are just so much bent in as to fall upon and coincide with it. That is "focusing" the lens, and the one image is now necessarily five times as bright as either of them was before. When the lens is in this position, we may go on pricking more holes, or take away the tinfoil altogether; and there is still but one image, though much brighter still, because so many rays are now converged to the same point.

It should be observed that, as in the case of mirrors, the spherical surfaces which are most easily ground do not truly converge the rays to a point, the figure necessary to do this being elliptic or parabolic. Such lenses have been ground, though with great difficulty. There are however other errors also to be corrected; and it is easier and more convenient to correct all these errors by methods presently described, or to stop off some of the most erroneous marginal rays.

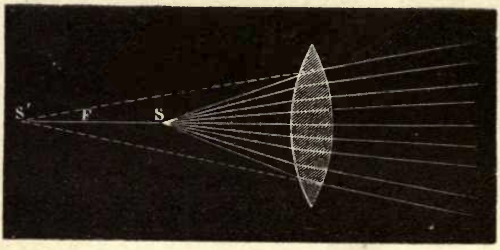

FIG. 52.—Lens and Virtual Image.

43. Virtual Images and Foci.—A mere inspection of Fig. 52 will show that if the object or luminous point be nearer the convex lens than its principal focus F, the rays cannot form an image, but simply become less divergent. If the emergent ray-lines are produced back to S′, that will be the "virtual" focus. There we have a virtual, magnified, erect image, as in the ordinary way of using a magnifying glass.[1]

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[1] The student is again strongly urged to work out for himself diagrams of this and other cases; not here described in detail, as unsuitable to the experimental character of this work.

44. **Concave Lenses.**—A double concave or other diverging lens either converts parallel rays into divergent, as in Fig. 53, or convergent rays into *less* convergent ones, which may be parallel, or still remain convergent. Such lenses can only have a "virtual" principal focus, F, obtained by producing back the divergent ray-lines into which they refract parallel rays.

A whole host of optical instruments, which cannot here be described,[1] are based upon these properties of lenses; especially microscopes, telescopes, and such lanterns as we employ in our experiments or for exhibiting views. In most microscopes and telescopes, a magnified image is further magnified by an eye-piece. In the lantern, the "condenser" lenses are employed to make the diverging rays from the radiant parallel or nearly so; while the objective, or our loose focusing lens, forms a magnified inverted image upon the screen of some object powerfully illuminated. Except as regards details necessary for correcting aberrations, the phenomena of refraction explain them all; and every curve of every lens has to be calculated for the special work which that lens has to do, according to its index of refraction and the law of sines.

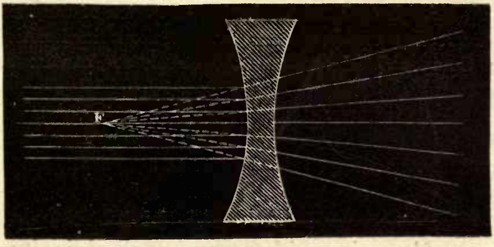

FIG. 53.—Concave Lens.

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[1] See Guillemin's *Applications of Physical Forces.* Macmillan & Co.

CHAPTER IV.

DISPERSION AND THE SPECTRUM.—DIFFERENT COLOURS HAVE DIFFERENT REFRANGIBILITY.

The Spectrum—Different Colours differently Refracted—and each Colour has its own Angle of Total Reflection—Position of the Prism and its Effect—Correction of Aberrations by Variations in Position—White Light a Compound of Various Colours—Colour can be analyzed—Suppression of Colour produces Colour—Artificial Composition of White Light—A Narrow Slit necessary for a Pure Spectrum—The Rainbow—Refraction and Dispersion not Proportional—Achromatic Prisms and Lenses—Direct Vision Prisms—Anomalous Dispersion.

45. **The Spectrum.**—With the water-prism before described, or a wedge-prism with faces of small obliquity, nothing more may have been noticed than the refraction described in the last chapter; though even with these instruments attentive observation will generally discover a slight fringe of colour at the edges of the refracted images. We must now, however, employ a prism of more density and greater angle—either the glass prism (Fig. 9), or the prism bottle filled with carbon bisulphide. Place in the optical slide-stage a perpendicular slit $\frac{3}{4}$ inch deep and $\frac{1}{8}$ inch wide, and arrange either the flint-glass prism, or the fluid prism on the stand, as in Fig. 54, first focusing the slit upon the screen; and, as we expect the rays to be now very seriously deflected, turning the lantern off at a considerable angle before interposing the prism.[1] What a

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[1] With a gas-burner the screen distance should not exceed about six feet. The arrangement in Fig. 10 is very convenient for these lantern deflections. An arrangement for considerably increasing the brilliance of the spectrum is described at the beginning of Chapter VI.

spectacle we have! There stands the glorious rainbow-band, as first revealed to Newton's enraptured eyes; and which is to introduce us to a new and magnificent field—that of colour. Of all the people who have experimentally studied Optics, and who of course have performed this experiment scores and scores of times, never one yet but has felt that it never loses its fascination; the same feeling of delight ever comes upon us, as that SPECTRUM appears on the screen (Plate II. A), which is to go with us, and be more or less our guide, through great part of our future experiments.

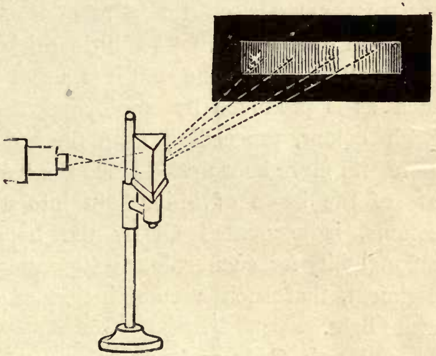


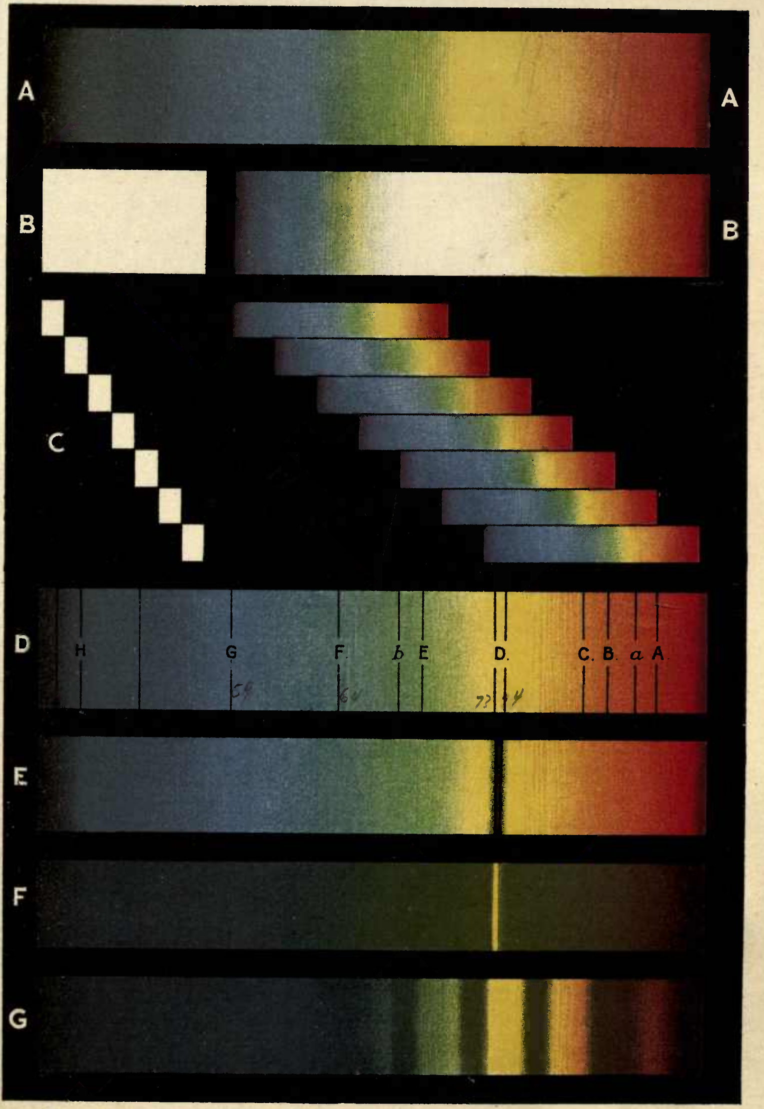
FIG. 54.—Production of the Spectrum.

46. **Different Colours differently Refracted.**—It is at once noticed, that while all the colours are bent aside, the red end of the spectrum is much less bent than the blue. Newton deduced from this and other experiments with the spectrum, that each colour of light had its own degree of refrangibility, and that white light was compounded of various colours.

We demonstrate the first point as follows. Arrange as before, but with a *short* as well as narrow slit in the optical stage—let it be, say, an aperture $\frac{1}{8}$ inch square—and let its long *narrow* spectrum be projected by the bisulphide prism. We may perhaps think that the effect of the prism is merely, of itself, to spread or open the colours. To see if this is the case or not, we adjust behind the first prism (*i.e.* between it and the screen) our glass prism in a *horizontal* position, with the refracting edge downward. If it were so, our spectrum would now be *generally* widened as well as refracted upwards. It is not, however; the violet end is refracted up far more than the red end, and the spectrum appears on the screen askew, or slanting. The spectrum may be perhaps a little thickened or widened, but that is all (it will not be so if it is a *long* or well-dispersed one, such as is produced by employing *two* bisulphide prisms). Each colour, proceeding from the red end, simply appears more and more bent up. Hence the "dispersion," or opening out of the beam of white light into a spectrum of various colours, is accounted for by the hypothesis of a different refrangibility for each colour; supposing only we find, on experiment, that such a combination of colours will compose white light.

47. **Each Colour has its own Angle of Total Reflection.**—Newton proved the special refrangibility of each colour by another still more beautiful experiment; one of the most elegant ever devised. It depends on the fact already noticed, that the angle of total reflection must vary with the index of refraction (§ 35); the violet rays being totally reflected (because more refracted), at an angle which would allow the red rays to leave the denser medium. Newton therefore arranged an experiment as in Fig. 55, except that he employed the parallel rays of the sun instead of those from the lantern. A perpendicular slit N is placed in the optical stage with the objective removed, or on the nozzle of the lantern if an adjustable slit is at command, and the parallel beam is sent through it (see Fig. 55, which shows all the arrangements in plan). As close to the slit as convenient, on a table-stand, simply "stood up" on their ends, are two similar right-angled glass reflecting prisms, P and P2, with their reflecting sides together, kept together by an elastic band passed round near each end; they must not, however, be in optical contact, and may, if necessary, be kept apart by a narrow slip of tissue paper. In the direct path of the rays from the slit, is a focus-

Pl. 2. THE SPECTRUM AND ITS TEACHINGS



A. *Spectrum of Incandescent lime*
B. *Wide slit, with its spectrum, showing white centre*
C. *Ditto. Ditto analysed*
D. *Spectrum of the sun.* E. *Absorption Spectrum of Sodium.*
F. *Emission Sodium Spectrum.* G. *Absorption Spectrum of Chlorophyll.*

ing lens, F, and beyond that, on another table-stand, is placed a bisulphide prism-bottle, B, in the usual position for throwing a spectrum on the screen, S S. In the path of the rays totally reflected from the film of air between P and P2, is another focusing lens, F, and beyond that, on a third table-stand, a second bisulphide prism-bottle, B2, which throws its spectrum on the screen, *s s*, adjusted at right angles to the other screen;

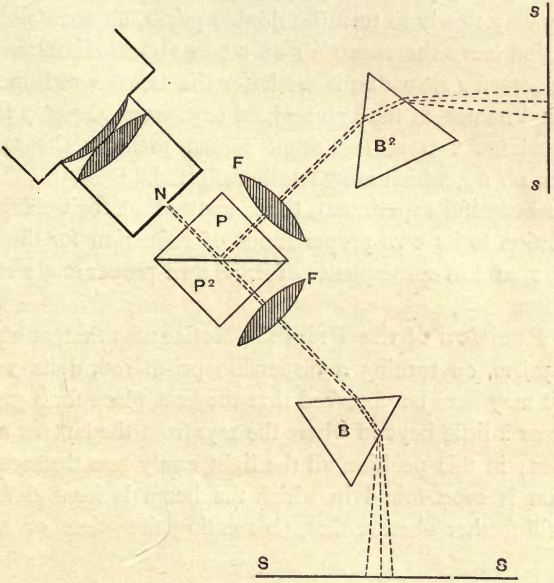


Fig. 55.—Newton's Experiment

or the screen *s s* will receive both spectra if the refracting angle of the prism B is turned the other way. All being thus arranged, the double prisms, P and P2, can be turned round their common perpendicular axis from right to left in the figure, till nearly all the rays from the slit pass through both, and the prism B throws a spectrum on the screen as usual. Except for a little loss by reflection and absorption, all is just as if P and P2 were not there, the *refraction* of one being exactly neutralised by the other, and the rays passing as if through one square bar of glass. Let now the double prism be very carefully and slowly turned round in the direction of the hands of a watch. At one certain point of revolution, just when the film of air meets the rays from the slit at the critical angle for violet, the violet *leaves the spectrum* on the screen S S, and, being totally reflected, appears on the screen *s s*.[1] Continuing very slowly to turn the double prism, all the colours in succession leave the spectrum on S S to appear simultaneously on the screen *s s*, so that if we letter the screens with the conventional names, at the point where one screen has only left on it the colours Y O R, the other screen presents the missing colours, *v i b g*, which are "totally reflected."[2]

This beautiful experiment, then, shows that each colour has in addition to its own proper index of refraction for the same medium, and in consequence of it, its own proper angle of total reflection.

48. **Position of the Prism.**—Notice next that, as with the water-prism, on turning a dispersion prism round its vertical axis (it may here be observed that the best place for a prism is nearly or a little beyond where the rays from the lantern appear to cross; in this position all the light easily gets through it), a position is soon found in which the beam is least deflected. But still further observe that, on rotating the prism on its axis

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[1] The effect is less visible on this screen, enough light being always reflected from the air surface to give a little spectrum. But it can be seen that the violet is strengthened.

[2] Only the sun, or the small radiant point of the electric light, will give the phenomena *perfectly* in these details. A large gas-burner will not answer for the experiment at all. A "mixed" jet will perform it fairly if the condenser will throw nearly parallel rays. The "blow-through" form gives too large a radiant for a good parallel beam; but even with that, it is at least easily shown, by taking both prism-*bottles* away, and leaving the rest of the arrangement, that at a particular angle the direct image of the slit is reddish, and the reflected one bluish.

in one direction from this position, the ray is not only more refracted, but more dispersed: the spectrum is lengthened, particularly at the violet end. Rotating in the other direction, while the refraction also increases, the spectrum is shortened.

49. **Chromatic Aberrations.**—This fact has an important application. If the prism refracts the blue rays more than the red, then a lens must do the same, and will bring blue rays to a focus nearer the lens than the focus for red rays. By placing in the slide-stage two apertures pretty close together in a black card, one covered with red gelatine and the other with blue, and focusing them on the screen with the large loose lens, it can readily be shown that this is the case; and thus, besides the "spherical aberration," already alluded to (§ 42), we have what is called "chromatic aberration," due to the fact that a single lens will not unite all colours accurately in the same focus.

50. **Correction of Aberrations.**—But we have here found a means whereby different *combinations* of even single non-achromatic lenses may be arranged so as to correct, to a considerable extent, both these aberrations. In detail, this must of course be worked out mathematically; but a simple illustration of a point which often puzzles students is worth while. We have just found that the effects of three prisms A, B, C (Fig. 56), of equal angles, variously inclined to horizontal rays coming, say, from the left hand, will be very different, not only in refraction but also in dispersion; and therefore these effects may be made largely to counteract each other. But such

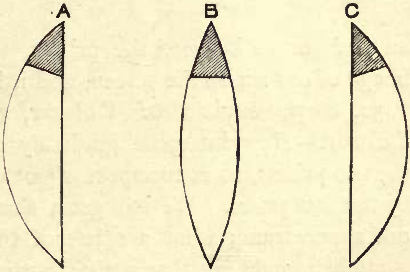

FIG. 56.—Effects of Position in Lenses.

prisms may, as before shown, be regarded as portions of simple plano-convex and bi-convex lenses. The arrangement adopted for our optical objective (Fig. 1) is one thus planned, to correct a great deal of chromatic and spherical aberration by very simple means.

51. **White Light Compounded of the various Prismatic Colours.**—Taking the different colours, as they leave our prism independently for the screen, or exist otherwise, we can show in many ways that when mixed together in proper proportions they produce white. First of all, arrange a second prism B as in Fig. 57, so as to intercept the dispersed rays, and bend them back again, but leaving an interval of half an inch or so between the prisms. We at once restore the image of our slit on the screen, and it is *white.*

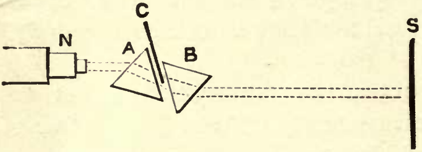

FIG. 57.—Recomposition of White Light.

52. **Suppression of Colour, the Chief Cause of Colour.**—Now interpose gradually a black card, C, between the two prisms, so as to suppress part of the spectrum produced by the first prism. We still get a sharp image of our slit, and not a spectrum; what are left of the coloured rays are accurately brought together again; but it is now a *coloured* image.

This teaches an important lesson that holds good through nearly all future experiments. It is, that we almost invariably *get* colour by, in some way, taking away or *suppressing* colour. If, instead of the black card, we interpose the edge of a slightly wedge-shaped prism, the colour taken away appears separately, and is always "complementary" to the other—that is, together they make white light. (§ 76.)

53. **Colour can be Analysed.**—The experiment further teaches a fact of transcendent importance in countless physical investigations. It is, that prism or spectrum analysis will always give us the exact actual composition of *whatever light there is* passing through the prism. If any colours be there, the dispersed spectrum will display them; if any be absent, their absence will be betrayed—it may be by immense gaps, or it may be by the narrowest lines. The truth of the analysis is only affected by the fact, that certain rays may be absorbed and so suppressed by the material of the prism itself. Such absorption has of course to be investigated and allowed for.

54. **Experiments in Compounding Colours.**—A convex lens will also compress the colours together into a white image; and a cylindrical lens will do the same. The latter may be extemporised successfully by using a confectioner's glass jar 6 inches in diameter filled with water.[1] Properly adjusted between the prism and the screen, this will compound out of the spectral rays a white, though not perhaps very sharp, image of the slit; and stopping off part of the spectrum will, as before, produce colour. If a cylindrical lens is used, it should be from 10 to 15 inches in focus, and will give quite a sharp white image.

Another beautiful and striking method is shown in Figs. 58 and 59. Get seven bits of looking-glass ¾ inch wide by 2 inches long. From a round wooden rod an inch in diameter cut discs, say ½ inch thick, as stands: to the top of each of these attach a bit of soft wax, and in this stick the end of a mirror, so as to stand vertically as Fig. 58. Arrange as shown in Fig. 59, standing the mirrors on a piece of blackened board, A, on a table-stand. First adjust the stand at such a distance that the rays from the prism P about cover the breadth occupied by all the mirrors together, and then take off all but one at the end, and adjust

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[1] In cold weather the water should be slightly warmed, else condensation of moisture upon the jar will interpose tedious hindrances to getting a good image.

that so that it may reflect its colour to a central spot on the screen, S. Put on the second, and turn that till its reflection occupies *the same spot ;* so of the third and the rest. Note the changes of colour as we add colour after colour ; till at last we have *white.* But take away—suppress—any one colour, and again we get colour.

Our next method depends on the persistence of visual impressions. We "see" things nearly a second after the exciting cause is gone—a long time, considering the apparently instantaneous character of all other light phenomena. Hold a slip of card in the diverging cone of light from the lantern ; it is a mere strip of bright white. Cut rapidly through the cone as with a sword ; it appears a white disc the size of the cone at the point of section.[1] Take, then, a white card circle, 12 inches

FIG. 58.

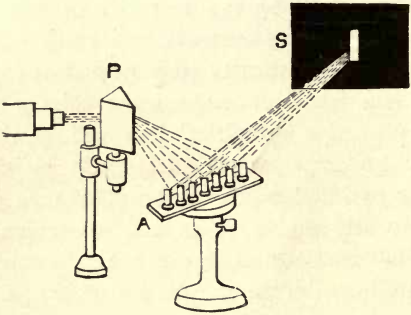

FIG. 59.—The Colours Recompounded.

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[1] I first saw this simple illustration employed by Professor Tyndall. Another familiar example is found in the circles of light produced by whirling round a lighted stick. Many toys of the "wheel of life" class depend on the same fact ; and slides can be procured from any optician by which the same phenomena can be excellently shown with the lantern. They are known as Eidotrope slides. Mr. Eric Stuart Bruce has introduced a very elegant demonstration. A long thin lath painted grey is rotated round its centre several times in a second. On this an ordinary lantern slide can be projected, appearing as a mysterious-looking phantom in the air.

diameter (Fig. 60), and divide into four quarters. On each of these paint in clear water-colours, as nearly as possible in the proportions of the spectrum, the spectral colours. We may not get them very correct at first, and it may be best to purchase the "Newton's disc," as it is called, of an optician; but some of such are too dark in the blue division. This disc is to be mounted so as to be rotated by a cord and simple multiplying arrangement, and then adjusted facing the lantern, so that all the light may be just about concentrated upon its face when the focusing lens is run fully out. If the disc of light is too large, place a circular aperture, cut in a black card, which will sufficiently reduce it, in the optical stage. This is important, for this fine experiment often fails because carried out by the general gas-light of the lecture-room, which gives very poor effect; whereas the full beam from the lantern brought on the face of the disc in a dark room appears quite differently. Now rotate the disc rapidly, and we get *white*, more or less bright, or greyish, according to the correctness of the proportions. Newton's disc can also be purchased as a glass slide for the ordinary stage of the lantern, and shows very perfectly in this way, but it is inferior to the painted card for the next experiment. We see, either way, that the presentation of a proper assortment of the colours to the eye, *anyhow*, so as practically to mix them, produces white.

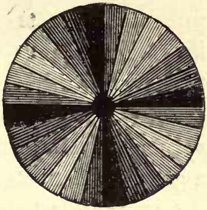

FIG. 60.

It is true, that white produced in this latter way is, by comparison, greyish; and hence some of those who pride themselves upon being "practical" colourists, and despise the scientific investigations of those they term "theorisers," have denied that white can be really thus compounded. It was recently stated in print by an "artist" that the experiment only succeeds at all with "pale washes," and only produces a poor grey then; and this was stated with sufficient assurance to pass for knowledge. But it was simply due to ignorance of two points. In the first place, so far from requiring pale washes, the *more vivid the colours are the better*, if in correct proportion; with some few discs I have seen a really good white produced. And in the second place, a grey is the necessary and simple consequence of a *deficiency of light;* as can readily be proved by gradually diminishing the light thrown upon a really white disc of card—it gradually becomes grey. Now assuming that the spectrum may roughly be divided into seven colours, and that our white is produced by the successive presentation of these to the eye, a moment's thought will make it evident that, at the very most, only *one-seventh* of the light that a white disc would reflect, can be reflected by the coloured disc. In reality, owing to absorptions explained later on, it is very much less; and hence our white must be more or less of a grey, if contrasted with a really white card.

Carry the last experiment a step further. Cut out from a circle of blackened paper, the size of the disc, radial sectors so arranged as to cover the same colours in each quadrant—say, the violets and blues—and fix them on the disc by a drawing pin at the end of each. We thus suppress colour; and as before, we get colour.

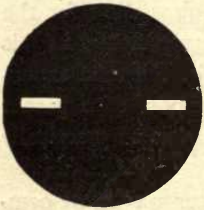

FIG. 61.

Again, prepare a disc of stiff, blackened card, as in Fig. 61, with two radial slots each 2½ inches long and about ¼ inch wide. Run a drawing-pin through the centre into the end of a stick, so that it can be rotated by the finger like a child's windmill, and hold the affair, or fix the stick in the Bursen clamp, so that each slot in rotating will cross the nozzle of the lantern, and so let a flash of light through. The nozzle itself must be covered with a cap in which is a similar slot, so as to make the flashes as nearly as single drop, we can trace what happens. This beautiful experiment was first performed with a sunbeam, by Antonio de Dominis, Archbishop of Spalatro, about 1600 A.D., though Descartes seems to have usurped the credit of his investigations, as he also attempted to do with the law of sines discovered by Snell. We take a small glass bulb $1\frac{1}{2}$ inch diameter, blown on a small tube, and fill it with water; or we may use filtered salt and water, for the reason that it not only increases the dispersion (§ 57), but diminishes the angle of deviation. The lantern must be turned *towards the spectator*, and placed farther back; the objective removed, and a blackened cardboard or other cap with an aperture the size of the glass bulb, placed on the flange nozzle; round which, or on which, by a hole cut in the centre, is placed a screen, S, of white paper or cardboard.

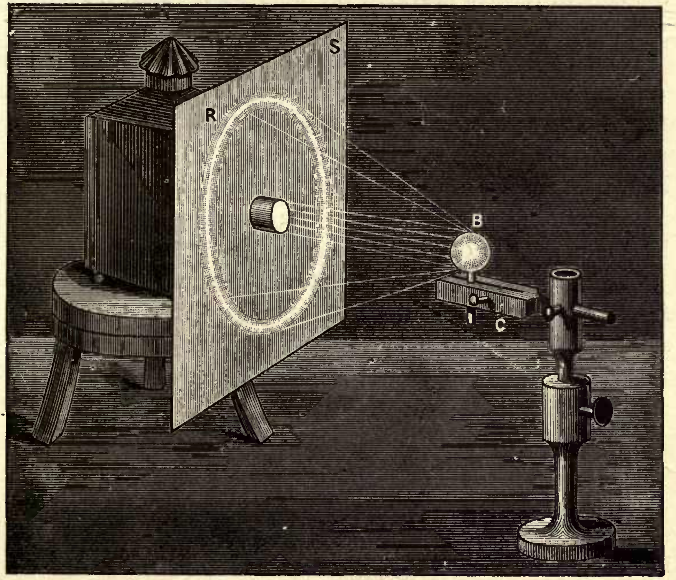

FIG. 63.—Rainbow Experiment.

Instead of a card cap, a revolving diaphragm with various holes may of course be used. Adjust the lime-light to throw a *parallel* beam on the bulb B, between which and the spectators place the blackened card screen (p. 18) to intercept the direct light. The bulb will be held in the clamp, C, by the stem, and both bulb and fluid must be brilliantly clear. We at once see a miniature "rainbow" reflected back upon the screen round the lantern nozzle, provided the bulb be not farther from the nozzle than about the radius of the screen.[1]

It hardly need be said that this rainbow is the real rainbow *reversed;* any spot on the screen where red appears, means that an eye there would *see red in the glass bulb;* and each other colour, unless the eye was moved, would need another bulb in the proper relative position: but the experiment does show correctly the emergence of a nearly parallel chromatic bundle of rays at one certain angle.

That such must be the case at one certain angle (about 40° for water) can be proved mathematically from the "law of sines," applied to the spherical bulb; and the demonstration of this is really due to Descartes. He showed that at one angle alone the rays, which at other angles of incidence emerged divergent and scattered, emerged as a *nearly parallel* beam, and thus produced conspicuous phenomena of *some* sort; the production of colour being afterwards explained by Newton's dispersion experiments with the prism. Fig. 64 shows in outline the course of the blue and red rays in both the inner and outer bow. The parallel rays, S S, from the sun, falling on the drop *b* at the proper angle, are refracted twice and reflected once, so as to transmit red light to the eye; and from the drop *a* (the angle *a* O *b* making about 2°), the blue rays being *more* refracted, also reach the eye; *a b* is therefore the apparent breadth of the bow. Other solar rays, S′ S′, by *two* internal total reflections and two refractions, also transmit coloured

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[1] This experiment will not succeed with a plain gas-burner, a strong *parallel* beam being necessary.

rays, but of course fainter; and these form the outer bow. An inspection of the figure will show that the order of colours in the outer bow must be inverted. Theoretically several secondary bows are possible, and with a very bright sun three are occasionally seen; but as a rule only the primary and the first outer and inner secondary are sufficiently brilliant to be visible.

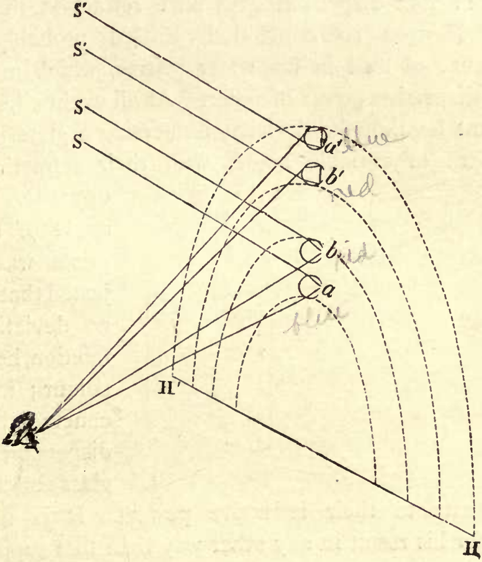

FIG. 64.

57. Refraction and Dispersion not Proportional.—Make a water prism as in Fig. 65, by cementing with marine glue two slips of glass 6 or 7 inches long and 2 inches wide into a V trough with angle of 60° with two partitions as well as two ends. If any difficulty about these, wooden partitions will do, cemented with black sealing-wax varnish. Fill one division with water, the next with saturated salt and water, the third with saturated sugar of lead in water. Place the horizontal slit in the optical objective, or on the flange nozzle, and focus on the screen; then pass the three fluids in succession across the beam. Observe that the water refracts and disperses it somewhat; the brine more; the lead most of all. The natural and first conclusion would be that the two effects are always proportionate: that dispersion goes *with* refraction in due proportion. Newton so concluded, misled probably by the frequent use of lead in his water prisms, which masked the very low dispersive power of water. At all events, he made an experiment he thought decisive, immersing a glass prism *in* a water prism of variable angle, with their refracting angles opposite. When the angle of the water prism was so adjusted that there was no deviation or refraction, he found no colour; and hence concluded that the dispersion of the glass and water were proportionate to their refractive powers. It is difficult to account for his result in any other way than that supposed; for when Dollond repeated this very experiment with glass and water, the result was exactly the opposite: viz., when the refraction was exactly counteracted, colour or dispersion *remained;* and when colour was banished a considerable deviation remained; a discovery that led at once to the construction of achromatic lenses.

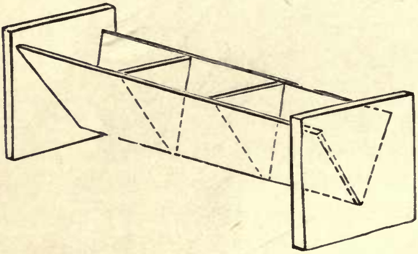

FIG. 65.

In fact, different media vary widely in the proportion of their dispersive and refractive powers. For its refracting or bending power, the dispersive (or spectrum-lengthening) power of carbon bi-sulphide is enormous; and if a prism bottle be filled with a solution of the double iodide of mercury and potassium, as described by Dr. Liveing, prepared of the utmost density, while the blue end of the spectrum will be absorbed by the pale yellow solution, the green and red are dispersed nearly twice as much as by the bi-sulphide. Flint glass, again, refracts light little more than crown glass, but disperses it nearly twice as much for the same angle.

58. **Achromatic Lenses.**—Here, then, we have the power of correcting or destroying chromatic aberration. Dealing with prisms as the simplest case of the problem to be solved, a flint glass prism of little more than half the angle (in fact, the proportion depends entirely on the density of the flint) will counteract nearly all the dispersion of crown, but leave a considerable amount of refraction. Such a double prism can be bought for 5*s*. Focus a slit on the screen as before, and on a small table-stand place on end the crown glass prism. We get as usual refraction and a spectrum; in this case rather a poor one, owing to the little dispersion of the crown glass. Now place next it, in contact, the flint prism, with its angle the reverse way: we still have the beam bent aside, but the *colour* is practically gone, and it is a white image of the slit, and not a spectrum, which appears on the screen. It is not necessary to explain in detail how this fact enables us to construct achromatic lenses.

59. **Direct Vision Prisms.**—Conversely, a prism of flint glass of about 52° (for average density), will counteract the whole refraction of a crown glass prism of 60°, but will so much *more* than counteract its dispersion, that there will be a considerable *reversed* spectrum. Hence we have the power of constructing "direct" prisms which give a spectrum without refracting the beam of light. Direct vision prisms composed of from three to five prisms of glass, are largely used in direct vision spectroscopes. For lantern work such prisms are very expensive when of large size, but Mr. C. D. Ahrens has introduced a prism as in Fig. 66, which answers our purposes at a very moderate price. G G are prisms of light glass,

enclosing between them carbon bi-sulphide, or phenyl-thiocarbimide as suggested by Mr. H. G. Madan, or cinnamic ether, B. One made for me gives a dispersion equal to a prism-bottle of 60° without any deflection, and is not only very handy to work with, as obviating any turning of the lantern aside, but more light passes through, and the spectrum is not at all curved.[1] Mr. Ahrens also constructs a prism made as in Fig. 67. Here G is one equilateral prism of glass, projecting into the cell of fluid B B. There being only one ordinary glass prism here, this is the cheapest large compound prism that can be made. It gives enormous dispersion—about 50 per cent. more than that of a prism-bottle—with very little, if any, more than ordinary deflection, and can be supplied unmounted for about 40*s*. Much more light traverses this prism than can get through the two prism-bottles generally used when great dispersion is required. A small direct prism of glass so mounted as to go into the nozzle of the optical objective, where the rays appear to cross, is very handy for many experiments, saving in some cases much adjustment of apparatus.

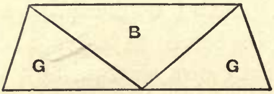

FIG. 66.

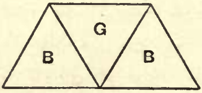

FIG. 67.

60. **Anomalous Dispersion.**—We have not even yet got to the bottom of this matter, however. We may obviously construct prisms of different substances, such as water or crown glass, and flint glass, of such angles that their respective spectra

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[1] With a single prism there is a perceptible curvature in the transverse lines or edges of a spectrum projected on a screen, owing to the convergence, and consequent various angles, of the rays traversing it. To get rid of this curvature in spectroscopes, is one object of the collimating lens. This brings to parallelism the diverging rays from the slit adjusted at its focus, which then traverse the prism at the same angle.

shall be of equal length. But if we do so we find the two spectra *do not agree.* There is more dispersion in one region than in another, as produced by one substance compared with the other; and hence *perfect* achromatism is almost impossible with only two prisms or two lenses.

Such variation in dispersive power may be elegantly illustrated by a modification of the transparency experiment described in § 38. Take the bottle-cell filled with powdered glass, rendered transparent in the way there described. Owing to the variations here considered, the refractive index of the fluid can only be brought *exactly* the same as that of the powdered glass, for some *one* colour of the spectrum; and the contents are not perfectly transparent for the other colours. Place therefore an aperture on the nozzle of the lantern, and focus it upon the screen with the loose lens; then interpose the cell filled with glass and fluid. The image will be still focussed fairly "sharp," of the colour formed by the small range of the spectrum which is corrected; perhaps a greenish image may appear; the other rays will be scattered, and form a nebulous halo round it of the complementary colour.

In some cases these differences in dispersion are very great, and Fig. 68 shows another form of direct prism for projection, constructed by Messrs. R. and J. Beck for Prof. S. P. Thompson, on a plan suggested by Wernicke, and founded upon this "irrationality,"as it is called. Cinnamic ether has the same *mean* refractive index as one of the new Jena glasses, but is widely different for the blue and red ends of the spectrum. A prism is therefore constructed by placing a very wide-angled prism F

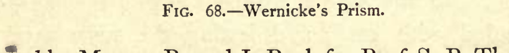

FIG. 68.—Wernicke's Prism.

of the glass, in a cell of cinnamic ether C C, closed by rectangular glass plates. The yellow ray is undeflected, but the red rays, R, and violet rays, V, are dispersed by the *second* face of the prism F as well as by the first, as shown in the diagram. This prism gives very great dispersion, and much better *definition* than carbon bi-sulphide, while the rectangular ends are an advantage. The cost of one not quite 4 inches long is about 5*l.* 10*s.*

But still stranger phenomena await us, to project which with the lime-light is rather difficult (it cannot be done with less; with the arc-light there is no difficulty), but can be accomplished by cementing into a deep glass trough, such as microscopists use for examining polyzoa, two thin glass plates A C, B C (Fig. 69) carefully made fluid-tight at the bottom and all the angles, but so that no surplus cement impairs the "knife-edges" of the two side compartments at C. Down the cell at C a strip should be carefully blackened so as exactly to cover the space occupied by the cemented edges of the plates, up to these fine edges and no farther. All the compartments are filled with alcohol; a slit is placed on the nozzle of the lantern and a parallel beam sent through it, focused on the screen by the loose lens; and just where the rays are most condensed the trough is placed, with the side C turned towards the lens, one end cell shaded with card, and letting the rays pass through the other cell *up to its extreme edge.* Now with a pipette drop into this end cell, drop by drop, a little saturated solution in the *same* alcohol, of the purplish-red aniline dye called Fuchsine. This arrangement is necessary to obtain the dispersion of the Fuchsine separately; as it will be seen that the alcohol cell A C B exactly neutralizes the refraction and dispersion of the

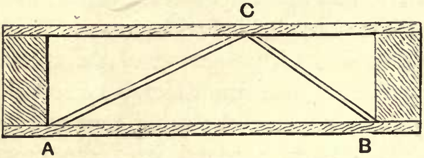

FIG. 69.—Plan of Trough.

alcohol in the two end cells. If we used a prism-bottle alone, filled with the dye, with a strong solution only red rays would get through ; while with dilute solution its dispersion would be overpowered by the more normal dispersion of the alcohol. As the dye is added in this way, the colours separate from the image of the slit, as we expect ; but if things are properly managed,[1] the red occurs, not at one end of the spectrum, but between the blue and the yellow, green being absent. Other substances give similar phenomena in various degree.

Though startling, however, these appearances are not really more wonderful, when we attentively ponder them, than that dispersive power should, compared with refractive power, differ *at all* in various substances. Our experiment with the Fuchsine simply shows us in a more exaggerated and startling form, the very same fact—whatever it is—which makes the dispersion of flint differ from that of crown glass. All alike reveal the "anomalous dispersion" of light. We can no longer maintain that the colours have even an invariable *order* of refrangibility. This is generally the case ; but we have now found that sometimes they have not.

And at this stage we must pause to collect our ideas. We

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[1] If the dye in the end cell is made too strong only red passes : if too dilute there is no visible dispersion. The use of the double cell is, that if the first be made too saturated, the other may be tried ; and for the same reason it is well so to adjust the glass partitions, as shown in the figure, which is the actual size, that the two may be of somewhat different angles, as 25° and 35°. The most brilliant jet should be employed, in order to work through as much as possible of the Fuchsine. Often the effect can be coaxed out of an apparent failure, by simply covering up, not only the other cell, but the thicker part of the one employed, so as to diminish the preponderance of red light which passes through, and may drown the much fainter blue and yellow. For private observation only, two small slips of glass may be inclined at an angle of say 10° by a strip of wood placed between them at one edge, and a drop of *strong* Fuchsine solution placed between them. Through this prism a brilliantly-lighted slit may be observed from a good distance ; and through such a small thickness even a solution strong enough to overpower the dispersion of the alcohol will allow sufficient of the colours to pass.

might account for reflection by a rough working hypothesis, which for years was more or less accepted, and was known as the Emission or Corpuscular Theory of Light. But even then we found difficulties in it. These are now vastly increased in many ways; and we find ourselves once more, by the mental constitution bestowed upon us, bound to ask the question: *What is Light?* We must frame some intelligible hypothesis by which we may string together the foregoing facts; and which if possible, may also account for such phenomena as we may yet further discover. This, then, will be the subject of the following chapter.

CHAPTER V

WHAT IS LIGHT?—VELOCITY OF LIGHT.—THE UNDULATORY THEORY

Light has a velocity—Velocity implies Motion of some sort—The Emission Theory—Transmission or Motion of a State of Things—Transmission of Wave Motion—Illustrations—Wave-motion and Vision—Analysis of Wave Propagation—The Ether—Refraction according to the Wave Theory—Total Reflection, Dispersion, and Anomalous Dispersion——Mechanical Illustrations.

61. **Light has a Velocity.**—If a man strikes a bright light, say ten miles off, we see it so instantaneously, that it is very difficult at first not to believe that we are, in some mysterious way, conscious of it the very instant it happens—that time has nothing to do with the matter. And that was probably the most ancient idea of the manner in which we "see" things.

But this idea was necessarily abandoned for ever, after a discovery made by Roemer in 1676. He found that, taking the calculated time for the eclipses of Jupiter's satellites, they always took place eight minutes earlier when the earth was nearest to them, and eight minutes later when it was farthest away; whilst if the earth was at either of the mid-points, they happened at the average time. He very soon drew the unavoidable conclusion, that light required about a quarter of an hour to cross the earth's orbit. This was soon after confirmed by Bradley; who calculated the very same velocity independently, as nearly as could be, from the apparent "aberration" of the fixed stars.

At a later period the velocity was actually measured instrumentally; first by Fizeau and Foucault, later by Cornu, since then by Professors Young and Forbes in Scotland, and Professors Michelson and Newcomb in America. The methods have been chiefly two. In Fizeau's method a ray of light is sent between the teeth of a toothed wheel to a distance of a few miles: and thence reflected back in the same path. If the wheel is rotated with a sufficient velocity, it is plain that while the ray has been journeying and returning a tooth instead of a space will have come to occupy its return path, and produce eclipse of the reflected ray. This effect must be gradual as the velocity is increased, as in Fig. 70, till total eclipse is produced; after this, if the velocity is further increased, the light will gradually reappear, to be again eclipsed; and the velocities of the wheel being known, the various eclipses will mutually check each other. Professors Young and Forbes thought that their experiments revealed the extraordinary fact that in air the velocity of red light appeared considerably less—perhaps one per cent. less—than that of blue, which if correct would involve the possession by our atmosphere of an extraordinary amount of anomalous dispersion; but Michelson and Newcomb, using a slit half covered with red glass, could not discover any such phenomena.

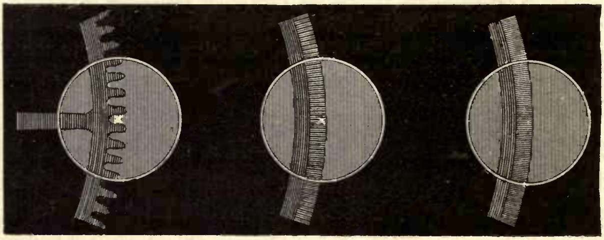

FIG. 70.—Fizeau's Experiment.

In Foucault's method, a ray of light, after passing cross-wires to serve as an image-point, proceeds any convenient distance to a mirror very swiftly rotated. It is thence reflected to a concave spherical mirror whose centre of curvature is the axis of rotation of the revolving mirror at the point struck by the ray. The ray is therefore reflected back in its own path to the rotating mirror; and if this is at rest or rotated slowly, it is again reflected in its original path of incidence, centrally upon the cross-wires. But when the velocity is sufficient, the mirror has rotated through a small angle while the ray has travelled to the concave mirror and back; and the return ray is therefore deflected to one side of the cross-wires through an angle double that of the rotation of the mirror (§ 24). This apparatus is so sensitive as to be applicable to distances of only a few feet; and hence, by interposing a tube filled with water between the two mirrors, Foucault was able to prove absolutely that the velocity of light was considerably less in water than in air.

All these methods give the very same velocity for light within quite a small percentage, much less than might have been expected in measuring such enormous velocities. The determination by Professors Young and Forbes is 187,200 miles per second, by Professor Michelson in 1882, 186,278 miles, and most recently of all by Professor Newcomb in 1884, 186,282 miles, the probable error not exceeding twenty miles.

62. **Light must be Motion.**—The velocity of light once proved, involves another point. Observe the absolute necessity of the case. At the moment one of Jupiter's satellites emerges from behind the planet it sends out, somehow, a ray of light—whatever that may be. At a given moment that ray from the planet P has reached the nearest point A of the earth's orbit. A quarter of an hour later it has reached the farthest point B. In the interval, *something* or other has passed from A to B. That passage of something from one point to another is obviously motion; and the con-

clusion that Light is Motion *of some sort* is an absolute intellectual necessity: there is no possible escape from it. It only remains to discover what the motion consists of, or what it is that is moved.

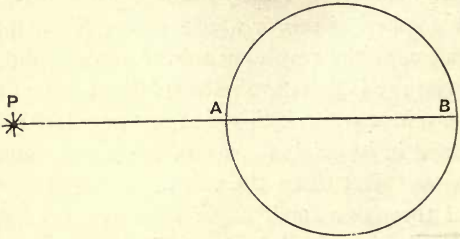

FIG. 71.—Light necessarily Motion.

63. **The Theory of Emission.**—The emission of very fine particles from the luminous body was, as we have said, the most natural idea; and it may be made to account for reflection, though encompassed even at that point with considerable difficulties. One of these we have considered already (§ 30); but it might be supposed that the luminous particles, to be seen, must actually enter the eye, and impinge upon the sensitive retina. But we have another and a greater difficulty, in the enormous *momentum* even the smallest particles must have, travelling at such enormous velocities as have been proved in the case of light. The weight of one grain would be equal in momentum to a large cannon ball as shot from the muzzle of a gun. Further still, what must be the *expulsive force* to produce such a velocity? And lastly, it is impossible to conceive of this expulsive force, and the velocity imparted, being the same for the largest and the smallest of all sorts of bodies, as is found to be the case. The feeblest candle-flame emits light at the same velocity as the enormous sun.

These difficulties might be partially evaded by supposing that the particles are so infinitely small, or otherwise so utterly different from common matter, as to have no relations of attraction with it; and, indeed, otherwise the propulsive or luminous body would, by its own attraction, gradually destroy the velocity, just as the earth gradually draws back a stone thrown up from it. But when Newton, who provisionally adopted this as a working hypothesis, though often leaning towards another next to be considered, sought to account on such a basis for some rays being refracted while others were reflected, the only way he could do so was to suppose that some particles reached the reflecting surface in a repulsive "fit," others being attracted. He was confirmed in this by the "law of sines." Versed in the mathematical laws of forces, so that at times he almost thought in mathematical terms, his keen eye saw at once that this peculiar law was a *law of velocity;* and he suggested, therefore, that the refracted ray was dragged down or attracted by the glass or water, and had its velocity *augmented* in the proportion of the "index of refraction." As is rather general in algebra, this proportion, equally with the reverse, accurately works out many optical problems. But it would follow that the particles *are* attracted by matter; and how, then, they can be projected with a velocity that never diminishes over stellar distances, is simply inconceivable. Finally, as we have seen, it has been proved rigidly, that the velocity of light is *less* instead of greater in the water than in the air. In absolutely proving this fact, Foucault and Fizeau absolutely overthrew the Corpuscular Theory, and *that* idea of the "motion" of light. We have therefore to explain in some better way why light is *refracted;* why at certain angles it cannot get out into a rarer medium, but is totally reflected (§ 35); and finally the strange phenomena—totally unknown to Newton—of anomalous dispersion (§ 60.)

64. **A State of Things may be Transmitted.**—Let us consider now another idea.[1] In Railway and Post Office we

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[1] For the idea of this paragraph, the simplest and most effective I have met with for illustrating what follows, I ought to acknowledge my indebtedness to Mr. J. Norman Lockyer, F.R.S.

have a very familiar example of actual Things being sent from one place to another, or from a sender to a receiver, at a given measurable speed. That may answer in many respects to the old Emission Theory of Light; and it is to be remembered that even in this case we must have some road or channel along which the sent Thing may pass, if it is not to be projected like a cannon ball. But let us think for a moment about a telegraph message. To quote Mr. Lockyer, here also "two instruments may be seen, one the *receiving* instrument, the other the *sender*. Between the office in which we may be, and the office with which the communication is being made, there is a wire. We know that a Thing is not sent bodily along that wire, as the goods train carries the parcel. We have there, in fact, a condition of motion with which science at present is not absolutely familiar: but we picture what happens by supposing that we have a *state of things* which travels. The wire must be there to carry the message; and yet the wire does not carry the message in the same way as a train carries the parcel. It is further remarkable that the wire carries the *state of things* along, very much quicker than the train can move—in fact, with a velocity commensurate with that Light itself."

65. **Wave-motion and its Transmission.**—Let us examine experimentally, then, another kind of actual motion. Make a large groove in a piece of board, or a light trough like Fig. 72 about a yard long, in which some elastic balls may roll; glass balls, or ivory bagatelle balls, will answer. First roll one slowly along: we can measure the considerable time it takes to go from one end to the other. Now place in the trough a set of 18 balls in contact; and drawing back one for some inches, roll it up to the rest at the same slow speed as before. Observe the difference. *Instantly*, to all appearance, the farthest ball now starts off as the first one strikes the row. It is not really so, for the

FIG. 72.

time can be measured by proper appliances; but the eye cannot discern any interval.

Now *this is wave-motion*, of one sort. The first ball struck is compressed, and then expands, so passing on the compression; and thus to the last. Each ball executes or has impressed on it *small periodic movements exactly like those of its preceding neighbour, but a very little later in time.* That is the entire essence of wave-motion; which may be of many forms, but with this property common to them all.

In the lantern we may illustrate this as in Fig. 73. Between two glass plates the size of the ordinary lantern slides, are cemented pieces of wood shaped to gentle curves as in the figure, of a thickness to just allow small balls of glass or ivory (or small steel balls from bicycle bearings will answer very well) to roll easily in the channels for them. In one, let a row of these balls rest, leaving the other clear. From the top of each slope let roll one of the balls. The one will be seen travelling across the screen: the motion in the other case will appear to be transferred *instantaneously* to the last ball in the series.

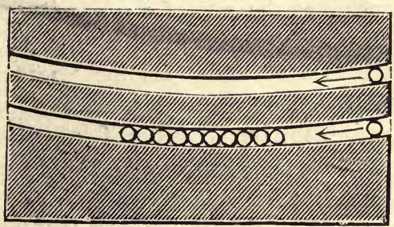

Fig. 73—Slide or Rolling Balls.

In a pond of still water, or in the middle of a circular sponge-bath filled with water, drop some small body, and study the beautiful phenomena. The spot into which the object fell is surrounded by a circular *wave* of water, which travels quickly outwards. This apparent motion is again very much quicker than any actual motion we could impart to the mass of water itself. It looks, too, as if the water were really proceeding outwards—being poured out as it were—from the central point. But if we drop one or two bits of paper on the water, we find it is not so : the paper only moves up and down. It has a very slight horizontal motion also it is true, but this too is not continuously outwards, but *to and fro*. In reality the paper at any point moves in an elliptic orbit ; but each particle moves in a similar orbit to its predecessor, a little later in time. Any one particle does not travel outwards, but *sets in similar motion the next particle*, and thus the *state of things* we call the wave is propagated.

It can be seen immediately, that if the motion of light be anything of this kind, we have got rid at once of our greatest difficulty, that of the enormous velocity ; for wave-motion is always much quicker than actual translatory motion. Across a deep open sea like the Indian Ocean, the great tidal wave moves at the rate of 1,000 miles per hour, though the water itself could move at nothing like it. In fact, if we can only find the idea otherwise fits the phenomena, we have got rid of nearly all our difficulties at a step. We therefore trace the matter further.

If the balls just now referred to were tied together by elastic threads, we should have a *return* wave from the last ball, since it would be sharply pulled back in its effort to escape. We have all seen this in an engine run up against a train, when each carriage or truck vibrates several times to and fro, giving us a picture of such waves in any *elastic* medium, such as sound-waves in air. These last give us our best example of this form of wave. In this case every particle of air moves to and fro in the direction of the wave, but otherwise keeps its own place ; and still the wave only, and not any particle of air bodily, moves onward. The fundamental property which characterises all true wave-motion is in this case difficult to picture clearly in the mind : but it is so important to do so, that we again have recourse to our lantern, which will place it before our very eyes. Get a circular glass plate, 13 or 14 inches diameter, mounted on an axle which can be turned. Exactly in the centre of the axle-hole describe a circle $\frac{1}{4}$ inch diameter and divide it into 12 portions, as in Fig. 74. (It is near enough to divide off into six by the radius, and bisect each division by the eye.) Arrange all firmly on a table, and having blackened the disc all over, take a foot-rule divided into eighths as a standard, and with a 3-inch radius strike or scratch a circle from say the top division. Extend the compasses exactly $\frac{1}{8}$th inch and strike another *from the next division;* then another $\frac{1}{8}$th inch, and so from the next division in the same direction, and so on, till we have gone twice round the divisions and struck 24 circles, giving us a band of scratches 3 inches across, with a little margin outside. (See Fig. 75.) Remove the objective and place on the flange-nozzle of the lantern a cap with a fine horizontal slit A B, 3 inches long, or a glass cap with a line scratched in black; and arrange the disc[1] in front of this, so that the band of circles crosses the slit as in Fig. 75. In front of all adjust the loose focusing lens, and focus on the

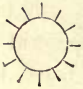

FIG. 74.

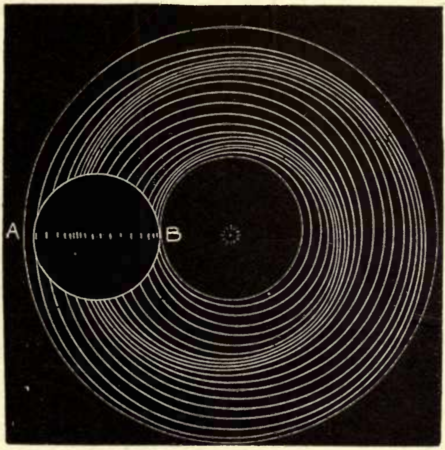

FIG. 75.—Crova's Disc.

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[1] It is known as Crova's wave-motion disc.

screen. On now revolving the disc we see a "wave" of alternate compression and expansion beautifully delineated in actual motion: and by keeping the eye on any one bright dot, the precise nature of the motion will be understood better than by all the description in the world.[1]

For reasons future experiments will make clear, the vibrations which constitute light are, however, to be considered as in one respect like those of water-waves, *i.e. across* the path of the wave, not in it. A disc with a wave-line round it like Fig. 76, will give a moving image of this if revolved across a blackened glass cap scratched with perpendicular lines all over; but a better way is to make a "slide" as in Fig. 77, consisting of a fixed blackened glass, A, in front of which are open grooves, B B, the whole length, for a panoramic glass, 18 inches long, to slide freely. The slide is kept together by a slab of wood, C, in which is an aperture for the blackened glass. On the blackened glass scratch perpendicular lines $\frac{1}{16}$ of an inch apart. On the long glass, also blackened, a single wave-line may be

FIG. 76.

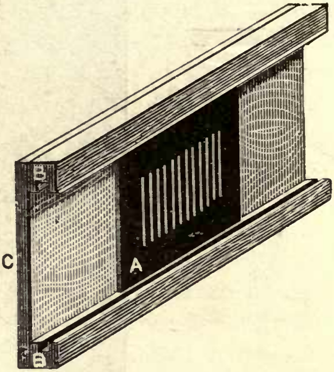

FIG. 77.—Wave Slide.

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[1] The private student may draw the lines pretty thickly in black on a white card, and revolve the card under a slit cut in another card.

scratched; but in order to show the interference of waves at a later stage, it is better for the sliding-glass to be in three widths, kept edge to edge by a thin brass binding at each end, and with *four* sets of waves as in Fig. 78, one pair twice as long as the other. The centre strip has a wave of each length; then by drawing it along through the binding the length of the *short* wave, it can be shown as drawn below, how the same given retardation brings the short wave a *whole* vibration, and the long one *half* a vibration, behind their fellow waves. It will be evident that when the whole arrangement is placed in the ordinary lantern-stage and focused, and the sliding part moved along, we shall have *moving* waves of white spots.[1]

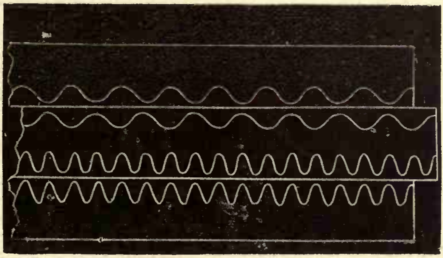

Fig. 78.—Movable part of Wave Slide.

Now it is to be again carefully noticed, that here also *no spot advances at all.* Every spot simply moves *up and down*, while the *wave-form* only advances across the screen, being due, as before, to the fact that each spot, representing an atom of ether, moves a *little later* than its predecessor in a similar path.

Thus we see that, by this kind of mechanism (actually proved to exist in the case of the ivory balls, sound, and

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[1] This slide was the result of much consideration; and after trying both, I consider it much superior in effect to the disc usually employed, besides being much more easily made and adjusted.

countless other motions), motion imparted at one end of a line of transmission is *yielded up* with enormous rapidity at the other, not only without any inconceivable motion between, but whilst things generally between the two ends, as in the case of our ivory balls, may almost seem to be in a state of rest.

66. **Wave Motion and Vision.**—It is not difficult to conceive how such wave-motion as that shown by our slide may affect the eye. We can easily imagine how longitudinal pulses of air beat on the drum of the ear D, as in Fig. 79; and if we imagine the retina to be furnished, as at R, with perpendicular rods standing up like a cat's whiskers, we can readily conceive how the transverse motion of the last particles in the wave should excite these. Those who are so happy as to possess whiskers, can easily prove by experiment that a brush across them yields more sensation than perpendicular pressure. Now it is remarkable that microscopical researches do show the retina to be studded closely with fine rods; and it appears probable that this is the true method of vision, or at least, that by which the optical image on the retina is transformed to consciousness in the brain, upon which our "seeing" Light *as* Light obviously depends. Several future experiments will lend much strength to this view; and another weighty confirmation of it is found in the well-known fact, that pressure on the eyeball produces the sensation of light.

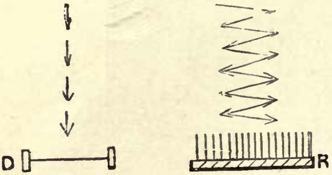

FIG. 79.—Sound Waves and Light Waves.

67. **Analysis of Wave Propagation.**—We have not solved all the problem, however. If light consisted of particles emitted, or if even wave-motion were only propagated in radial lines from each centre (and this is how some people quite erroneously understand the Undulatory Theory), it will be

obvious that as the distance increases, the radii must separate as in Fig. 80, and we should have spaces between them with no wave-motion. Yet we see an unbroken circle of waves in our pond; how is this? Figs. 81 and 82 supply the answer. In Fig. 81 let us consider a wave direction, A B, from the luminous centre A, and suppose the wave arrived at the particle B. The next particle *in the same line* to receive the motion will be C. But C only receives it because it is the *next* particle; and obviously the next particles D and E are just as near, and in the very same kind of contact; they ought also to receive the motion. They do, and the consequence is that every vibrating particle over the whole sphere surrounding the wave-centre becomes a new centre like B for another sphere F G. In Fig. 82 let us consider the waves from the centre L to have reached the circle M N. Every point in this circle sends out fresh circles of waves, shown on the curve O P. Analysis, however, shows that all these secondary waves destroy each other by mutual interference (see Chap. IX.) except in the grand circle O P, where they reinforce each other; and thus the curve O P remains, as in a pond, the grand "front" of a collective or main wave. If, however, we interpose a screen, at O O′ P P′, which stops this main wave, then the subsidiary waves which go to make it up are only partially

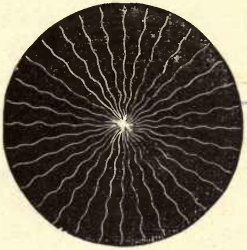

Fig. 80.

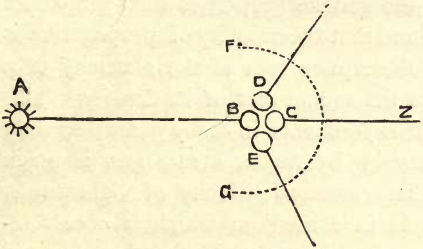

Fig. 81.—New Centres of Wave-Motion.

destroyed by interference, and appear at R S, as in the diffraction fringes hereafter to be seen (§ 113). Most of the difficulties found in comprehending the wave-theory are entirely owing to not understanding this "construction" of the waves; and it is hardly too much to say that while, on the one hand, any apparent objection that can be brought against the Undulatory Theory applies with equal or more force to *any other* theory; on the other hand, any rays, when isolated and studied by themselves in detail, behave exactly as the theory would lead us to expect. The correct analysis of these details of wave-propagation is originally due to Huygens.

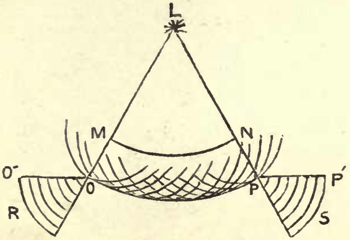

FIG. 82.

68. **The Ether.**—If, however, waves are sent from distant stars to our eyes, and elsewhere, there must, as in all the preceding cases, be *some medium* through which they are propagated. We know by experiment on other wave-propagations, such as those of sound, the general properties such a medium must have; since it is found that the velocity of propagation is directly proportional to the square root of the elasticity of a medium, and inversely as the square root of its density. This has been proved by rigid experiments in many gases; so that, for instance, the velocity in hydrogen, a rare gas, is much greater than in air. The *enormous* velocity of light-waves, therefore, is only possible in a medium which is *almost* infinitely elastic, and at the same time *almost* infinitely rare; and yet which is not quite so (or time would not enter into the question of distance at all) but has a *definite proportion* between these two functions. It cannot be attenuated air, but must be something far more rare; since we can keep air out of a glass vessel, while light passes through glass and many bodies, and

through the best vacuum we can form; moreover we know that air absorbs or stops light considerably, and hence light could never reach us, through the rarest atmosphere, from the enormous distances of the stars. Still further, attenuated air could not give us those *definite* velocities with which we have to deal, but must give a widely different one from that in denser air; nor finally, is the proportion of its elasticity to its density anything like great enough.

We have therefore to conceive of some still more rare and subtle medium which fills all space, and which is called the Ether. We shall hereafter see that we are obliged to attribute to it other physical properties quite different from those of an atmosphere.[1]

But though this ether easily permeates all we call matter, it is easy to conceive of its particles, and those of matter, hindering and otherwise acting on each other, or communicating motion to each other. Wind passes freely through a hedge of trees; but still the trees hinder or "slow" it, while yet again the wind moves the trees; and conversely, if we could shake the trees, we should cause a wind. Such, in brief, is the conception or hypothesis of the ether as held by physicists.

69. **Explanation of Refraction.**—Refraction now is easily explained. Any beam of light, as we have seen, has a main *wave-front across it*, and it is obvious that in meeting any refracting surface obliquely, one part of this wave-front will meet it before another. Conceive, then, that while the ether permeates the open structure of all matter, it is still *hindered* in its motions by it, as the wind is hindered, but not stopped, by the trees. Then trace a beam A B (Fig. 83) to the refracting surface C D, marking off any assumed length of its waves by the transverse lines. The front will be *retarded* at E before it is retarded at F, and we will assume the retardation to be such

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[1] Some attempts have lately been made to dispute the existence of an ether (see *Phil. Mag.* April 1879, and July, 1881). The objectors have not borne in mind the essential physical necessities of the case.

that the wave from E in the denser medium is only propagated to any shorter distance G, while in the rarer medium it travels from F to H. It is plain the beam must swing round; but when the side F also reaches the denser medium, the whole will be retarded alike, and the beam will proceed as before, only slower and in a different direction. The theory so far exactly fits the phenomena; and when we come to polarisation it will be easily seen why the beam is *divided*, and part reflected while part is refracted (§ 129).

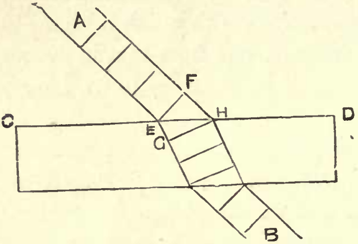

FIG. 83.—Refraction.

70. **Total Reflection Explained.**—Total reflection can be explained by mathematical analysis, and is so explained by Airy, while it is impossible to explain it by any other theory that has ever yet been framed. Airy shows that, beyond a certain angle, no *main* wave can emerge, while the small secondary waves perish immediately by interference (Chap. IX.).

71. **Dispersion Explained.**—The different refrangibility of different colours is easily accounted for. According to both Emission and Undulatory theories the measurements agree; and those who believed the Emission theory, had to consider the red particles as larger or stronger than violet ones, as we have to consider violet waves only half the length of red ones. But as all colours of light seem to move with equal velocity in ether, violet waves must make *two* vibrations for each one of red. If, then, the vibrations are retarded at all in a refracting medium, on the face of things those which occur twice as often will (as a rule) be hindered most; they have more of the hindered motion to perform, and, therefore, must be more refracted, provided there be nothing so peculiar in the arrange-

ments of the molecules which retard them, as to affect them otherwise.

72. **Anomalous Dispersion Explained.**—But there may be relations in the retarding molecules of matter which do affect the ether-motions peculiarly, and so cause "anomalous" dispersion. We cannot suppose that the *lengths* of the waves for each colour preserve under all circumstances a uniform proportion; for we have not only seen they do not, but our very theory of refraction is based on the supposition, that the wave-lengths are *shortened* by retardation in a refracting medium. The only supposition possible is, therefore, that the *number* of vibrations per second, or their *time period*, is the determining constituent of colour, as it is of musical notes (§ 81). Now we shall find strong presumptive proofs hereafter (§ 84) that the molecules of different bodies, like small pendulums of given lengths, have in fact their fixed and proper time-periods of vibration. And we can thus very easily conceive how certain relations of these respective periods to each other, or of the lengths of the waves to the distances between the molecules, should cause molecules of matter to hinder or assist in very various degrees, the differing periods of vibration in the ether-waves. Cauchy has even shown mathematically, that dispersion at all, or the fact of different colours being differently refracted, can only be explained if the distance from molecule to molecule be fairly comparable with the length of the waves. (See § 121.)

An analogy may make this clearer. Imagine a line of soldiers marching across a hard common. On reaching a piece of heavy ploughed ground, their steps (representing wave-lengths) would be retarded and shortened. Imagine also a line of little children—it is easy to understand that on the hard ground they might keep up with the men easily. On reaching the heavy ground they too would be retarded, and probably retarded *more* than the soldiers, their shorter and feebler steps thus representing the greater retardation in most substances of the shorter waves of light. But when at the sea-side some years ago, I happened to notice that on a particular piece of shingly beach my little boy was actually retarded or hindered in his pace *less* than I was—there was something in that piece of beach which somehow hindered less the period and weight of his steps. Just so the molecules of some substances may be of such sizes or at such distances, that they are specially favourable or unfavourable to waves of certain character, as in anomalous dispersion.

73. **Mechanical Illustrations.**—We may illustrate practically many of these points by mechanical means, due to German ingenuity.[1] Though not "lantern" experiments, they are easily seen by a whole class, and vividly illustrate the subject. We are dealing with *motions*, supposed to be in free ether *equal* at any two points of a wave-front exactly transverse to the direction of the ray. It is obvious this is a purely mechanical problem, and that we may mechanically represent it with fair accuracy by two equal wheels revolving freely on two ends of an axle, and left to roll down a slightly inclined board. Let Fig. 84 represent such a pair of wheels, the axle being made of $\frac{1}{2}$-inch iron, turned down at the ends to about $\frac{1}{8}$ inch, on which revolve freely but accurately boxwood wheels about 2 inches diameter, with rounded rims. These dimensions were found best by Mr. Tylor. It is obvious that while rolled along the smooth board such an apparatus will preserve one

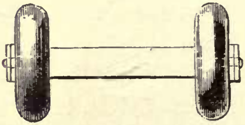

FIG. 84.

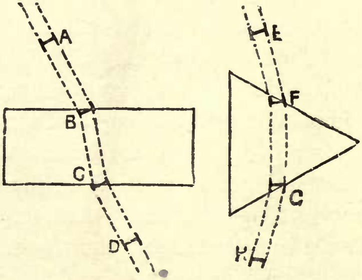

FIG. 85.

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[1] Described by Mr. Tylor in *Nature*, Jan. 1, 1874.

direction. But referring now to Fig. 85, let there be glued on the board a rectangular and a triangular piece of the thick pile plush called "imitation sealskin." If this is presented to the wheel-track the right way of the pile, it will retard the motion considerably, and when the track A B is oblique, the wheel that first meets the plush being first hindered, the track will swing round to the direction B C, and on leaving the plush resume the track C D, exactly picturing the course of a ray of light through a thick piece of glass. The triangular piece in the same way represents a prism, the track E F being refracted to F G, and thence to G H. Nay, even *dispersion* may be thus pictured by having a second pair of wheels, S (Fig. 86), of smaller diameter, to represent shorter waves—say 1¼ inches to 1½ inches. These wheels will be found perceptibly *more* deflected from S F to the track F K. The wheels may either roll freely down a slight incline, or may be held back by a thread at the centre of the axle. Finally, *total reflection* may be illustrated as in Fig. 87, for it will be found that if the track A B leaves the edge E F of the velvet at a certain angle, the wheel C, which first emerges, gains so much on the one still upon the velvet, that the axle swings right round and proceeds on the track B D.

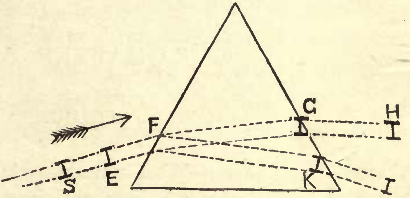

FIG. 86.

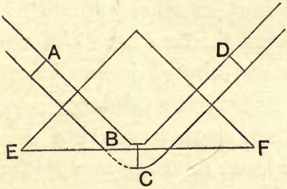

FIG. 87.

These illustrations will sufficiently enable us to grasp the main points of the wave theory. Some other points will arise later on; but we shall now resume the experimental study of colour.

CHAPTER VI

COLOUR

Absorption of Colours—What it means—Absorbed, Reflected, and Transmitted Colours—Complementary Colours—The Eye cannot judge of Colour Waves—Mixtures of Lights and Pigments, and their Difference—Primary Colour Sensations—Not the same thing as Primary Colours—Colour as we see it only a Sensation—Experiments showing merely sensational Colour—Doppler's Principle.

We have now cleared the way for another class of experiments, for which, to work with comfort, we must somewhat alter our arrangements by removing the objective, and placing on the flange-nozzle of the lantern a black card or other cap with a perpendicular slit cut in it rather longer than we have hitherto worked with—say $\frac{1}{8}$ inch to $\frac{3}{16}$ inch wide by $1\frac{1}{2}$ inches long.[1] A long slit, owing to the convergence of rays by the lens, gives a perceptible curvature across the spectrum band; but this need not matter to us. Arrange the loose focusing lens F (the one of longest focus if there are two) so as to focus the slit on the screen. The lantern must then be deflected, as for all prism work (unless a compound "direct" prism is used) and adjust the prism P otherwise as before. The whole arrangement is shown in Fig. 88, and its object is simply to produce on the screen the spectrum of a slit upon which we can more readily make various experiments.

We require throughout the experiments in this and the next

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[1] A brass cap with adjustable slit is, of course, much more convenient.

chapter to have the most *brilliant* spectrum we can get, especially whenever a narrow slit is necessary. To secure this we *converge* light upon the slit, by arranging the latter at the focal point of either a cylindrical or spherical lens. This can be mounted in a wooden frame, so as to go in either the ordinary slide stage, or the stage of the optical front when that is used, choosing a focus which will converge the parallel or already slightly convergent rays from the condenser, upon the slit. The converged rays will of course diverge again after passing the slit; but the focusing lens will collect them. Such an arrangement is not absolutely needed, but greatly adds to the brightness of the spectrum.

74. **Absorption of Colours.**—Providing now some coloured glasses, or some strips of coloured gelatine between

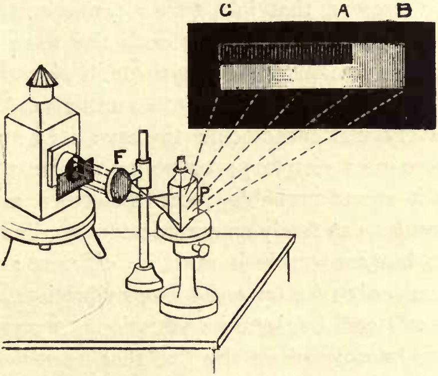

FIG. 88.—Spectrum Work.

glass plates, we make some experiments which teach us a very important lesson. We are apt to think that the sunlight which comes through a red glass window is all *turned into* red—made red. Well, there is the spectrum of our complete or white light on the screen, drawn out into its constituent colours. Over half the slit hold a bit of the red glass; if the light, or most of it, is really "reddened," all the spectrum ought to be turned into red. It is no such thing, however. There is no colour in the spectrum of the glass, *where that colour does not exist in the ordinary spectrum;* the sole effect is that certain colours are cut out, or absent. We get the colour, as so often before, by *suppressing* colour. If the glass is a pretty pure red, only red, and a little orange, A B, is seen in the spectrum of the half slit covered by the glass; all the rest is cut away. So of all the other gelatines or glasses, but we soon find it is very difficult to find a *pure* colour; generally there are left, at least, two well-marked colours; and if we unite just those portions of the ordinary spectrum, by employing proper slits in proper places, and uniting the colour passing through them by our confectioner's jar, or a cylindrical lens (§ 54) we get the same colour as the coloured glass.

We see, therefore, that in passing through a transparent body, its molecules take up or absorb the waves of certain periods, and the remainder passing through give the colour of the body. This is not at all difficult to understand. We have supposed every matter-molecule to have its own period of vibration (see next chapter); or perhaps more often several periods, as it seems probable most molecules are complex. These molecules can freely communicate any vibrations to the ether-atoms, but conversely it must be different: the matter-molecules can only take up *synchronous* vibrations. That one tuning-fork will communicate its vibrations to another of the same note we know; and we also find that when thus giving up its motion to the second, it loses its own more quickly than a fork that does not. A fork mounted on a unisonal resonance-case sounds louder, but *stops sooner*, than one unmounted: it has been imparting its motion to the unisonal column of air, and in so doing exhausts its energy. See then what must happen. If waves which produce red sensations require vibrations of 450 million millions of times in a second, and such rays pass with others through matter whose molecules vibrate at that rate if set in motion, these molecules must take up or absorb those particular vibrations from the ether, and the rest passing through give a colour due to the residual rays—in this case green.

We shall examine tests of this theory presently; but meantime, however absorption is produced, many other experiments will show that the colour of our glass is produced simply by the absorption of certain colours. Throw a good long spectrum on the screen—through two prisms if the light is powerful enough—and provide some large squares of the coloured glass or gelatine. Say we have a red one. Walk up near to the screen and hold the square in the hand by one corner in the red rays; it stops these very little, or is "transparent" to red rays, which it permits to reach the screen. Move the glass along in the spectrum, however, and gradually we find it casts more and more shadow, till at last the shadow is *black;* the glass is absolutely opaque to such colours of the spectrum; it absorbs them all.

We soon find also, that as absorption increases, not only the shade, but what we call the "colour" itself, often changes, more and more of the spectrum being cut out; as indeed we should expect. With marine glue cement together a few glass troughs, of plates about 4 inches square, and tapering from $\frac{1}{2}$ inch to 2 inches apart. Make solutions of chlorophyll (green leaves in alcohol, pretty fresh), permanganate of potash, picric acid, ammoniated sulphate of copper, oxide of copper in ammonia, and bichromate of potash. Try first the chlorophyll. The thin end cuts out all the blue half and some bands in the red end; pass to the thick end of the same, and the light transmitted is probably only the extreme red. A very few experiments of this kind with other solutions will show how wonderful are the powers of this "spectrum analysis," for such it is, and how complex are most of the colours of natural bodies; and will prepare us for the further details of the next chapter.

75. **Absorbed, Reflected, and Transmitted Colours.**—But meantime a further lesson of the same sort. We should expect from the foregoing that colour transmitted through bodies, would often differ considerably from colour reflected by them. A red glass, since it absorbs the green and blue and transmits the red, reflects hardly any, and appears by reflected light almost black, as do some other colours. In some cases the colours reflected and transmitted are nearly complementary (§ 76), but seldom quite so; because even reflected light has penetrated some distance among the molecules of a body, and thus been partially subject to their absorbing influence, or had certain vibrations taken up by them. Two very simple and pretty examples will sufficiently illustrate this. Place a single film of gold leaf smoothly between two glasses $2\frac{1}{4}$ inches by 4 inches, and bind round the edges to save from injury; or place it between two discs of glass mounted with putty in wooden frames that size. Deflect the lantern at right angles with the line to the centre of screen, throw the light on the gold leaf[1] at 45°, and focus it with the loose lens on the screen; we get the yellow reflected image. Now place it in the optical stage, direct the lantern to the screen, and focus: we get a transmitted *green* image. Take, again, a clear glass, and another blackened at the back; and cover each with a film of any red ink which owes its colour to aniline dye. When dry, place in the optical stage the clear glass: it transmits a fine *red* image. The blackened one reflects (when treated like the gold leaf just now) a beautiful *yellowish green* image. And the clear glass illustrates the usually compound nature (*i.e.* partly transmitted through a portion of the substance and so partially absorbed, and partly reflected) of reflected light, by giving a *reddish orange* image.

We can easily prove by experiment that the colours we see

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[1] In focusing such surfaces by reflected light, all the light from the nozzle should be concentrated on the surface, and some small mark, such as a black dot, sharply focused on the screen with the loose lens.

in natural objects are chiefly residuals left after this internal absorption, or are colours to which the bodies are transparent. Get any flower which shows a full green leaf, and rich red petals in largish masses, such as a tulip; and we soon find we cannot "see" its colours, unless they are either placed in white light, or in the appropriate colours of the spectrum. Throw once more on the screen the prismatic band, and move along the tulip in its rays. In the red rays the red flower shines bright red, and the leaves possibly dull red (owing to the peculiar spectrum of chlorophyll, which transmits the extreme red as well as the green). But as we move it along the red becomes black, and the green changes also, precisely as the spectrum did when we cast upon it the shadows of our coloured glasses. Highly coloured chromo-lithographs, moved along in the spectrum, yield very instructive phenomena of the same kind. As mentioned presently, two superposed cells containing acid copper sulphate and potash bichromate, allow a pure green only to pass; and by this light a drawing executed in red and yellow chalk appears *black.*

76. **Complementary Colours.**—We have found that we make white light by compounding together all the colours of the spectrum; but we have also found that we may produce white with much less; for in the experiment with seven little mirrors (§ 54), many of the prismatic rays were of necessity omitted. We carry this method of experiment further, and arrange our prism as before, with either a cylindrical lens (or the water-jar as such), or a large bi-convex lens [1] so focused as to re-form a white image on the screen. Now prepare two black cards with slits $\frac{1}{2}$ inch wide and $1\frac{1}{2}$ inches long, and insert them, as in Fig. 89, in a strip of blackened wood, with a saw-cut in it, so that we can slide and adjust the slits at variable distances: provide also two other pieces of card by

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[1] A lens 6 inches diameter and 14 or 15 inches in focus is excellently adapted for such experiments as this, covering with card or paper all but a horizontal band 2 inches wide across its face.

which these half-inch slits can be narrowed to any less width required. Introduce this just at the back of the re-uniting apparatus, and, first covering up one slit, arrange the other so that only the blue rays pass through it, giving, of course, a blue image. Next, uncover the other slit, and carefully sliding the second card to and fro, we can find a position (somewhere in the yellow or orange-yellow) and a proportionate width of the two slits, which *again makes the image white.*

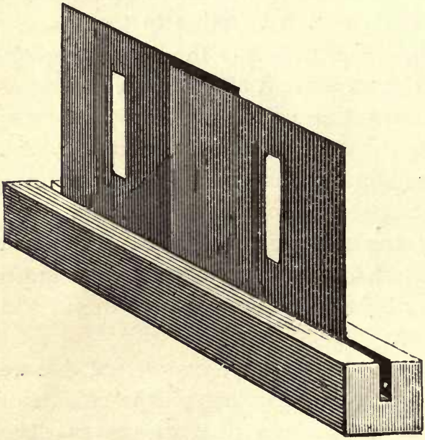

FIG. 89.—Slits for Complementary Colours.

Continuing these experiments with other colours, we find that for almost any colour near one end of the spectrum, there is another towards the other end which, with it, makes white, and is accordingly called its "complementary colour." And notice that we can do this with our *really* "pure" spectrum colours. It is not as in a former experiment (§ 52), when we divided the whole spectrum by a wedge-prism into two coloured images; for those two colours really were themselves compounded, and between them contained *all* the coloured rays. But here two *single* colours make white; and hence we learn that we may have a white, undistinguishable by the eye from any other white, which will not, on prismatic analysis, yield more than two colours. We may, by continuing these experiments, find that a white may be compounded of three colours, or of more. We never get a white unless there are waves of *more than one* period; but either white, or almost any colour, may be compounded out of various constituents.[1]

77. **The Eye unable to judge of Colour Waves.**—Now this is another cardinal, fundamental fact. It teaches us a wonderful truth, which still more remarkable experiments will confirm : viz. that colour and light, *as we see them*, are not only purely matters of sensation, or subjective consciousness; but that this consciousness is easily deceived, and quite incapable of distinguishing between whites and colours very differently constituted. We cannot tell "by the eye" that the blue-yellow white differs from seven-colour white; nor can we tell by the eye that a compound blue, containing nearly one-half the whole spectrum, is different from a pure spectrum blue, which may be of the same apparent shade.

78. **Mixtures of Light and of Pigments.**—And there is another strange thing. The old artists always considered that blue and yellow and red were "primary" or simple colours, and that blue and yellow made green. But here are blue and yellow, and instead of making green, they make white! How is it they ever make green? To solve the question, we fill one of our glass cells with solution of picric acid—apparently a pure yellow—and hold it in front of half our slit, as in previous absorption experiments. It allows not only yellow to pass, but *nearly as much green*, absorbing all the other rays. We take a rich blue glass, and analyse that in the same way. This apparently pure blue allows blue, and *as much green*, to pass, absorbing nearly all the rest. This itself is strange enough—that when we add green to both blue and yellow we should be unable to detect it by the eye. But it is obvious now that if we place both colours in the path of the beam, one *after* the other

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[1] A slit in the red, one rather wider in the green, and a broad band in the violet, will give a white of three colours. A rather narrow slit in the red, and one double the width in greenish-blue, will give a white of two colours. A narrow slit in orange-yellow (just the red side of the D line) and a rather broad band in full blue, also give white.

the yellow solution will stop the blue rays which get through the blue glass, and the blue glass will stop the yellow; but *both allow the green to pass*, and the net result is therefore that colour. It is the same with powders and paints; the light penetrates some little distance among their particles (§ 75), and is absorbed in the same way; and the green we get is the survival, or net result after the absorption by both, mixed with some white light reflected unchanged from the outer surface.

But get another lantern, or use both nozzles of the biunial if such is employed, and place the ordinary objectives on both. Place in the ordinary slide-stage of each a black card, with an aperture which shows, say, a 2-feet disc on the screen; arrange that the two discs partly overlap, and hold in front of each objective one of the same two colours, or the blue may be a cell of the sulphate of copper. In this way, it is obvious that instead of the light on the screen being the *remainder* of two successive subtractions or absorptions, where the discs overlap it is the light from both colours *added*. And the result now from these two same colours is not green, but — white.[1] Analogous effects may be shown with a good grass-green glass, chosen by trial, and the beautiful purple solution of permanganate of potash.

As some may still have difficulty in realising that successive absorptions are the real cause of our ordinarily getting green by combining blue with yellow, or orange-yellow, we may make another striking experiment, which would seem to be a crucial test. Our previous blue and yellow allowed green to pass through each, as shown by spectrum analysis, and therefore green was what may be called the sole "surviving" colour. But, by search, we may find solutions which will give very

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[1] It is possible to get a solution of ammoniated sulphate of copper so pure a blue as to transmit hardly any green, when the green half of the experiment, with that particular solution, would naturally fail; but get either solutions or glasses of a good blue, which transmit green as well as their blue and yellow, and the same materials will do for both.

similar colours to the eye, but of another prismatic character. Make a solution of oxide of copper in liquor of ammonia.[1] This, too, is blue, and its spectrum, A C (Fig. 90), shows that it allows to pass, beside blue, nearly all the green; in fact, all the spectrum to the point B. Make another solution of bichromate of potash, which is a deep or orange-yellow. This allows the red and yellow end of the spectrum to pass, from the point E, with only a trace of green, if any; and by a little dilution of one or other solution, or the use of a wedge-shaped glass cell for each, the amounts of these two colouring matters can with care be so adjusted that the spectrum of one begins about *where the other ends*, and there is no sensible portion transmitted by both. Now here are a blue and a yellow very similar to the preceding; and their discs, when overlapped, produce, like them, a fair white, or nearly white. But superpose these two cells across the nozzle of the same lantern, and we get no longer green as we did before, but black; the two stop the light altogether. Similar effects may be produced by Chance's "signal-green" glass, and another coloured a good red by copper oxide.

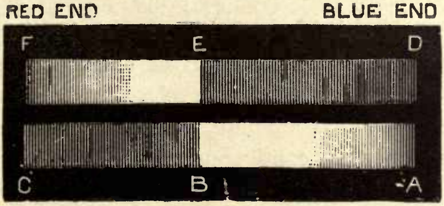

FIG. 90.—Complementary Absorptions.

These experiments explain a fact familiar to painters in water-colours, which as a rule are more or less transparent colours, showing very largely by the white light of the paper reflected *through* them; as may be seen by their colour on the

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[1] Acid solution of copper sulphate with the bichromate allows pure green to pass.

paper differing widely from that of the cake. Hence brilliance of colour can only be got *by a single wash*; every successive wash stops out more and more of the white light; and several washes, of the proper spectral colours, instead of producing white as in the Newton's disc (§ 54), or as even a mixture of colours in *one* wash sometimes will, rather produces a muddy grey approaching black. The final result can only be the colour which is allowed to pass by all the washes, which is very little. As Sir John Herschel expresses it, the water-colour painter[1] really works chiefly by *destroying* colour, and therefore uses as few washes as he can.

Even with pigments painted in water-colour on white paper, the same facts may be proved by proper arrangements. If we mix on the palette bright cobalt-blue and the lighter chrome-yellow, a wash with the mixture gives us a good green, by the double absorptions among the particles already described. But so long ago as 1839 Mile found, that if rather narrow and long stripes were painted contiguously of each alternate colour separately, and then blended on the retina by removing the eye to a proper distance, the result was not green, but either a white or rather yellowish-white, according to the shades of yellow and blue.[2] Or the colours may be blended in larger patches by a double-image prism,[3] or in other ways. Any

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[1] What is here said applies far less to oil painting, which deals with more solid layers of pigment, unaided by a white background.

[2] I have seen a statement by a "practical artist," who accompanied it with much hard language about "scientific theorizers," that such stripes when so blended gave *green*. All that can be said about such an assertion is, that as a general rule, with really good blues or yellows, it is simply not the fact: the statement is due to sheer lack of experimental investigation. Some blues and yellows are so *saturated* with green in addition to the blue and yellow, that after the two latter have combined into a white, the green heavily predominates. Such will of course give green; but approximately pure and bright blues and yellows cannot be made to do so; and examination of the blue-greens which do, through a prism, will reveal at once the great preponderance of green which causes the exception.

[3] § 122.

tolerably pure blue and yellow will always, when their coloured images are *added*, produce white or near it, and cannot anyhow when so added be made to produce green.

79. **Primary Colour Sensations.**—Nevertheless it is considered probable that there really are three primary colour sensations, though different from the blue, yellow, and red of the old artists. Helmholtz and Maxwell believe the three primaries rather to be violet, green, and red, neither of which can be compounded by any mixtures of colours, but which in combination can be made to produce any of the others. A narrow slit in the green between the *b* and E lines (Plate II. D), and a broad band in the violet rather to that side of the G line, can in the way described in § 76 be made to give a blue, which accounts for nearly the whole half of the spectrum from the blue end, when combined, appearing of that colour. Yellow appears to the eye such a "pure" colour, that it is difficult to believe it can really be compounded. We have seen already, however, that it will bear mixture with a very large quantity of green without the eye detecting that mixture; and it is easy to show by experiment that red and green will produce it. One method is a very pretty one easily demonstrated by any double lantern. From one nozzle project a spectrum by any of the arrangements which have been described; from the other focus on the screen the image of a perpendicular slit in a black card in the ordinary slide-stage, long enough for the image to project some obvious distance above and beneath the spectrum, when thrown upon it. Place in the stage with it a pretty pure red glass, and move the slit so that the red image may travel along the spectrum—somewhere in the green we shall get a fair *yellow*. Again take a green glass selected by trial with the slit, and somewhere in the red we shall again get a yellow.

A second method is to compound, in the way described in § 76, a wide slit in the red, and a still wider slit in the green extending *beyond* the *b* and E lines. This will give a yellow from the prismatic colours.

Another method is due to Lord Rayleigh. A film of blue gelatine stained with litmus is placed between two glasses; prismatic analysis, by methods already described, shows that it cuts out all the yellow and orange rays. A similar yellow film coloured with aurine cuts out all the blue and violet. Both together, it will be seen, stop out all but the red and green. Now take away the prism, and let the light from the lantern pass direct through both, and we get an *orange-yellow;* so that here we actually have apparently blue and yellow glasses producing neither green, as in one previous experiment, nor white, as in another, nor black, as in another—but by successive absorptions, *orange-yellow!* And in all cases prismatic analysis of the glasses or other coloured substances separately, perfectly accounts for all the phenomena. A still better combination is a cell of litmus and one of potash bichromate, which gives purer residuals—so pure that if a small aperture is focused on the screen through both cells, the prism will disperse the yellow image into two nearly sharp discs of red and green.

But observe, we say three primary colour *sensations*, and not three primary *colours*. The distinction is very important. So far as the actual spectrum and spectral colours go, even Newton's seven do not represent the case; every point in the spectrum differs somewhat in shade from its neighbours, and each one has its own distinct period of vibration, on which the colour (and other properties also) depends. No one is any more "pure" or "primary" than the other. But there are generally believed to be in the retina of an ordinary eye three *main sets* of nerves, or of the fine rods already referred to (§ 66), or whatever else receives the impacts of the ether-waves and translates them into consciousness; one responding mainly to violet, another to green, and another to red. But tuning-forks, to take one obvious analogy, will also respond, though in a much less degree, to *other* than their own proper notes; and so it is supposed these sets of nerves, rods, or other mechanism also respond in less degree to other wave periods than their own. It is then conceivable that periods which give, let us say, a pure spectral yellow, should also act on the brain by partially exciting the red and the green rods; and we should of course expect that if these red and green rods were simultaneously excited by their own proper colours, they would conversely produce the same sensation of yellow, or nearly so, as in the other case. The same reasoning would apply to other colours; and will account for blue and yellow alone making white. For if the blue waves excite the violet, blue, and some of the green, while the yellow waves excite the green and the red, the two together set in motion to some extent the apparatus which responds to all the colours of the spectrum. However the exact details may be worked out, the remarkable phenomena of colour-blindness, and the fact that they are almost entirely confined to blue, green, and red colours, make it very probable, if not certain, that in the main this view is the true one.

80. **Colour merely a Sensation.**—The obvious and striking consequence at once results from such a theory, that colour is merely a *sensation*. We have already made many experiments which confirm this view, and prove that our sensations are by no means trustworthy guides; but we can now demonstrate that it is so by still more striking experiments, whose nature is easily understood. We have (§ 66) supposed vision to be excited by motion communicated transversely to the ends of fine rods, with which the retina is studded, and so communicated through the nerves to the brain. Now, if we press a rather blunt pin-point on any part of the body, or excite sensation in any other way, we feel it at first very vividly; but by degrees the feeling deadens, and we take no notice. The nerves which respond to that particular feeling are by exercise, for the time, *fatigued*—tired out—and can no longer do their work. That is the reason we wear our clothes without feeling them, and of many similar facts. Now if we suppose some of the rods to respond, like tuning-forks, to certain vibrations or colours, and other rods to others, we ought to expect, under

similar circumstances, results of the same kind. Demonstration of this is the object of our next experiments. Two lanterns may be used, one to illuminate the screen the moment the other is shut off; but one is to be preferred, as more certain, for the first two experiments at least. Remove the objective, and prepare a black card 3 inches or 4 inches square, with a circular hole in the centre, which, when held against the flange-nozzle, as at N, Fig. 91, and there focused on the screen, gives a disc of about 18 inches diameter, or 12 inches for a short screen distance. Arrange the loose focusing lens F in front, to focus it accordingly, as in Fig. 91, and of course when the card

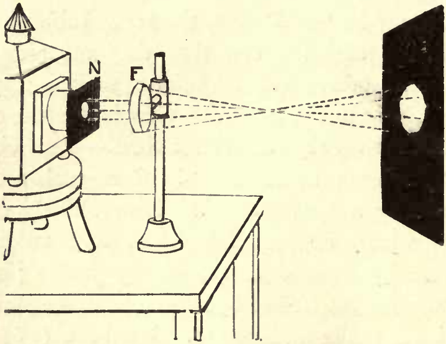

FIG. 91.—Subjective Colours.

is removed the *whole* screen is instantly illuminated. Have ready also a piece of good red glass, the size of the card, the picric acid cell, and a blue glass. First we hold the plain card over the nozzle, as shown in the figure, while we count twenty rather deliberately, fixing the eyes meantime intently on the *same point* in the bright disc. After twenty or twenty-five seconds remove the card suddenly, and where the disc was, we now see a *dark* circle on the illuminated screen. The exhausted nerves no longer respond to the stimulus of the white screen, as do those over the untired area; and hence, though all the screen is equally white, where the bright disc was it appears dark.

Repeat the experiment with the red glass held over the card, removing both together. Here the fibres or nerves which respond to red vibrations are alone fatigued; the others are not. Hence when the glass and card are withdrawn, and the screen illuminated with white light, the red rays of that light can no longer excite in the tired nerves such vivid sensations as the other colours, which act upon fresh and rested nerves; and so, after a second or two, the place where the disc was appears *green*, though no green light is really there, except as a component of the white. In the same way, hold the picric acid cell in front of the card for twenty seconds, and we get a spectral blue; while the blue glass gives us a yellow. We "see" a colour which *does not exist*, except in our nervous sensations.

There is a still more striking experiment of the same class—that of projecting upon the screen the *entire spectrum*.[1] Arrange the bisulphide prism as for so many previous experiments, but using now for brilliance as wide a slit as will give fairly pure spectrum colours; and arrange that a tolerably brilliant gas-light can be turned up instantaneously at a given signal. Project the spectrum on the otherwise dark screen, but in this case count thirty; and be sure vision is fixed, by placing a small black mark to look at about the middle of the spectrum. At the word "thirty," cover the lantern-nozzle, while an assistant

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[1] I believe this beautiful experiment was first performed by Professor Tyndall at Glasgow. Seeing the expressions of misgiving with which he introduced it even with the electric lantern, I was somewhat surprised to find that with the lime-light the effect is all that can be desired; and that with a screen distance of about 6 feet, and a good bisulphide prism (with a glass one the spectrum is not long enough), it can be satisfactorily shown even with an Argand gas-burner, on one condition—that the screen is not too brilliantly illuminated afterwards. Hence the illumination of the screen by an ordinary gas-light during the second stage, instead of throwing upon it the full beam from the lantern.

turns up the gas; and we see on the screen the *complementary spectrum*, solely due to fatigue of the organs of vision.[1]

With the aid of contrast, a mere shadow will deceive sensation in the same way. Arrange a powerful gas-burner rather nearer the screen than the lantern, and considerably to one side. Throw on the screen a strong light from the lantern, with a strong red or blue glass in the stage or held over the nozzle. After a few seconds hold a card with pattern-apertures cut in it in the coloured rays, the gas-burner being turned up at the same instant. Where the shadows fall, the screen is free from coloured light, and is illuminated by fainter *white* light from the other source. But the shadows appear by contrast strongly tinged of the complementary colour.

If further proof be needed of the distinction between the physical realities which underlie light and colour, and our purely sensational consciousness of them, it is at hand. Some people are more or less "colour-blind," while yet the perfect optical images must be formed on the retina. Some few have absolutely no sense but that of light and shade, though the physical reality is the same for them as for us. What the world appears to them, we may demonstrate by lighting our room with a Bunsen burner, in the flame of which dry carbonate of soda is held, or still better, a morsel of sodium in a spoon, or for a large hall a handful or two of tow saturated with salt dissolved in diluted spirit and with salt rubbed into it, may be ignited in a wire basket held for safety over a basin of water. All is mere light and shade; and we can see, as we turn up the ordinary gas, what we should miss, without the colour-sense, from our beautiful world. Again, a large dose of the medicine *santonine* affects the colour-sense considerably,

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[1] There are a few with whom these experiments do not succeed. Some of these are colour-blind, while others seem persistently "unable" in all such matters; and the whole nervous system of some is so vigorous, that the retina does not really become fatigued; but nine-tenths of any average audience find no difficulty.

and, besides distorting other colours, making nearly all persons incapable of perceiving violet and purple. This strange fact is easily accounted for if we conceive that the drug renders the rods of fibres attuned to the quicker vibrations so relaxed, that for the time they only respond to slower ones.

81. **Doppler's Principle.**—Final illustration of this is given by the verification of a principle pointed out by Doppler in 1841, and which also demonstrates that it is solely *period* (§§ 72, 93) which determines a spectrum-colour. If an observer, and any body originating waves (of any kind) are rapidly approaching, the wave-periods appear quickened; in the reverse case lengthened. With sound-waves, such apparent changes in period affect *pitch*. Accordingly the whistle of a locomotive sounds very much sharper whilst an observer in another train approaches, than when the trains, having passed, are receding. And more directly, by causing a sounding tuning-fork to excite sympathetic vibrations in another at some distance, the rise in pitch when either fork is made to approach the other, can be directly demonstrated.

In light, similar changes in wave-period affect *colour;* and a swiftly-approaching coloured star would appear of a shade nearer the blue end of the spectrum. The eye is unable to judge directly of any such differences in shade; but the "lines" in their spectra described in the next chapter (§ 87) give, as it were, divisions of a micrometer-scale for measurement; and by these we are enabled to see that every part of a spectrum actually is displaced under such circumstances. This actual shifting of the "lines" enables us to measure the velocity of an uprushing solar flame; or to determine that a star is approaching or receding from us at a given rate; or to affirm that a star which in the telescope appears single, is really double, and that its component stars are revolving round each other with definite velocity. This important means of investigation has within the last few years opened up an entirely fresh department in astronomical science.

CHAPTER VII

SPECTRUM ANALYSIS

Continuous Spectra—Absorption Spectra—Their use in Analysis—The Solar Spectrum—Line Spectra—Reversed Lines—Radiation and Absorption Reciprocal—Fraunhofer's Lines—Reversed Solar Lines—Thickened Lines—Solar, Stellar, and Planetary Chemistry.

However much we disperse the spectrum of our lime-light or gas-burner, from the narrowest slit, we fail to find any dark bands in it; it is an unbroken band of colours, insensibly shading into one another (Plate II. A). Such is called a continuous spectrum, and it is found that *any* body which can be heated to incandescence without being vapourised—that is, which glows while retaining a solid or liquid form—gives this kind of spectrum. If we heat a piece of iron, for instance, it gives out first only *red* light—the longest and slowest waves. As we heat it more, yellow is added; then gradually green and blue; but the spectrum is always *continuous as far as it goes.* A gas flame does not give us by ordinary methods the spectrum of a vapour, but that of the *solid* particles of carbon in a state of incandescence: hence the continuous spectrum. This rule has been found universal. Many substances are volatilised before they can be made to give a complete spectrum: but if whilst solid they can be heated so as to emit light at all, it is an unbroken spectrum so far as it extends, and it commences from the red end. Thus the body emits the *slowest* vibrations first, gradually acquiring the quicker ones; which we recognise in popular language when we say it first becomes red-hot and then white-hot. A thermometer moved in the spectrum will show us that still longer and slower waves than the visible red waves extend beyond the red end, and are even hotter than the red. So that a body, heated, first acquires comparatively slow vibrations, which are too slow and long in their waves to excite vision; gradually it adds quicker and quicker ones; till at a certain point, different for each body, the motion of the molecules is so rapid as to overcome the attractive forces, and they fly apart in vapour.

We have now to examine phenomena of another class. In all experiments to demonstrate lines or bands in the spectrum, care must be taken that the spectrum is focused on the screen all along its range. The phenomena cannot be displayed otherwise; but it requires the careful adjustment of the focusing lens. The best means of securing this is roughly to adjust the focusing lens and prism so as to get the spectrum on the screen; then to hold a fine wire across the slit, and finally adjust the lens in focus, and *incline it* to one side or the other, until the shadow of the wire appears as a black line *equally in focus* from one end of the spectrum to the other.

82. **Absorption Spectra.**—Some of the experiments in the preceding chapter have really been experiments in spectrum analysis, of precisely the same nature as are half of the experiments made by microscopists and chemists every day. A large part of their work consists in the examination of mere "absorption spectra" such as we have already seen upon our screen. We may demonstrate its nature by many homely and instructive experiments. Filling, for instance, our glass cells with known samples of genuine claret or other wine, we obtain, by the method already described, a spectrum with certain dark bands. Now we can easily obtain other solutions, compounded with more or less alcohol, and coloured with various substances, which, "to the eye," are of exactly the same colour. But the

imitative solution will not give the same absorption spectrum. It *cannot be made* to do so, inasmuch as the vibrations absorbed depend on the synchronal vibrations of the very molecules themselves. It is needless to give more examples, or to explain how we have even in this method of analysis a powerful and delicate means of detecting adulteration, in any substance which admits of being presented as a coloured solution, or any other transparent form. We have only to ascertain the absorption spectrum of a sample of known purity; and the spectrum of the sample to be tested will at once reveal if it be genuine or adulterated.

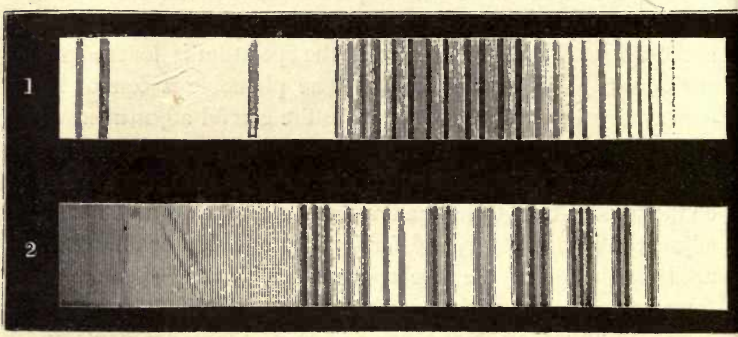

FIG. 92.—(1) Iodine Vapour. (2) Nitrous Gas.

Again, if healthy blood be somewhat diluted with water, a characteristic absorption spectrum will be observed with all the blue end cut out, and two broad bands in the yellow and green, near the D and E lines to be presently explained. But if we now hold in front of the slit a trough filled with blood *poisoned* by almost anything—say by carbonic oxide, or prussic acid—we shall perceive a marked difference in the spectrum. Light will be a Revealer of the poisoning to which the blood has been subjected.

Coloured gases or vapours contained in closed tubes will give very characteristic absorption spectra. A closed tube containing some iodine, vapourised over a lamp and held in front of the slit, gives a very beautiful spectrum; as also does one filled with nitrous gas (Fig. 92). The latter gas can be easily produced by putting some copper-turnings in a test-tube and pouring on them some nitric acid. Carefully avoid inhaling the fumes.

A small piece of glass containing didymium or erbium, or a small bottle filled with solution of didymium sulphate, can be hown to be nearly colourless; but when held in front of the slits will give remarkably distinct and characteristic absorption bands.

83. **The Solar Spectrum.**—We cannot show the solar spectrum in the lantern, but every student should see the leading phenomena for himself. Provide sufficient black cards to go all across a window, as a black band about a foot high resting on the middle sash or bar; they need not be fastened, as the only object is, for the width of that band, to stop out the light, and a little overlap of loose sheets will effect this. In one of the middle sheets cut a slit not more than about half an inch wide and five or six inches long; and choosing a day when the sky is brilliantly lighted, and the slit standing out against it, or at least against a bright white cloud, take the bisulphide prism, and observe the slit through it from the other side of the room, or from a distance of not less than eight or ten feet. The spectrum will be plainly seen to be crossed by several well-marked dark lines, as represented in Plate II., Fig. D. By employing more prisms to increase the dispersion, and examining the image with a telescope, these lines are increased to hundreds; but most of the few in the plate can be seen with the single prism-bottle and nothing else.[1]

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[1] It does not seem generally known that the principal lines of the solar spectrum can be perfectly well seen by this simple means. Even with a "lustre" of pretty good flint glass, I have never failed to see the D line, and the chief line in the blue. For further detail of spectroscopes and spectroscopic work, see *The Spectroscope*, by J. N. Lockyer, F.R.S. (*Nature Series*). This chapter only deals with the physical outlines of the subject.

Now we have the best of reasons to believe that the sun is incandescent : his amazing heat alone makes the supposition a necessity ; and his spectrum is moreover, to the eye alone, unless widely dispersed, so very *near* to a continuous spectrum as to make it almost certain, upon that ground also, that the light emitted from him originally must be from incandescent liquid or solid. What, then, is the cause of these dark lines ? The probability would appear to be, from what we have seen already, that they are in some way due to absorption.

84. **Line Spectra.**—We examine next the spectra of *coloured* flames, or flames which contain the *vapour* of solid bodies. The metal sodium is a convenient substance, being so easily volatilised, and the vapour so readily made incandescent by a moderate temperature. A spirit-lamp with salt well rubbed into the wick will show the line fairly well ; but if more brilliance is required, slide back the burner or lime jet, and introduce at about the point it usually occupies, a short Bunsen burner. In the flame of this hold in a small platinum spoon a pellet of sodium. The spectrum arrangements being all ready as before, we see on the screen simply a *bright yellow line*—the characteristic line of sodium, known as the D line or lines. All the rest is dark ; the sodium-vapour gives a pure yellow light.[1] (Plate II., Fig. F.)

Now, it is found that all incandescent gases give such "line" spectra ; as if, when their molecules of matter were so dissociated as to be able to behave independently, they had their own periods of vibration, like pendulums of a fixed length. Some give more lines than others—sodium itself

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[1] In every experiment involving combustion of sodium or other substance in the *optical* lantern, care should be taken to protect the face of the condenser by a plate of thin annealed glass or a film of mica ; otherwise morsels of the substance in a state of fusion are apt to splutter on to the lens and inbed themselves in its surface. I have in *Optical Projection* described a simple kind of combustion lantern burning the substances close to the slit without any lens, which was devised by Professor Weinhold of Leipzig.

gives an additional line with the more intense heat of the electric arc; while with wide dispersion, the yellow line is seen to split into two lines close together. But incandescent gases give *line spectra*, and no gas or vapour gives the same lines as any other; so that when Mr. Crookes some years ago found in the spectrum of some lead-refuse volatilised, a new green line which none of the known metals had yielded, he knew that he had something before him that had hitherto been unknown, and pursued his investigation till he had separated the new metal Thallium. As in previous instances, Light was to him a true Revealer of the unknown.

Lithium and strontium are pretty easily volatilised in the shape of their chlorides, and a small quantity of these salts will show bright line spectra in a Bunsen burner, or even if placed on the wick of a spirit-lamp. For a combustion lantern, burning the substances in a metal capsule or spoon close behind the slit, Prof. Weinhold gives the following recipes, a little heap of the powder being placed in the capsule, in which heap is stuck a cotton wick soaked in lead chromate: this is lighted, and in a few moments the powder will flare up and give its line spectrum. For sodium lines: 3 parts sodium nitrate, 1 part potassium chlorate, 1 part shellac. For calcium: 2 parts chalk, 10 parts potassium chlorate, 3 parts shellac. For strontium: 3 parts strontium nitrate, 1 part potassic chlorate, 1 part shellac. For barium: 3 parts barium nitrate, 1 part potassium chlorate, 1 part shellac. The shellac to be powdered separately from the salts, which are also to be rubbed down to powder, and the two mixed previous to use with a horn or wooden spoon.

Good line spectra can be projected with the oxy-hydrogen flame by Professor Edelmann's method. A "blow-through" jet is arranged with a vertical nozzle, over which can be adjusted by a sliding ring hollow carbon cones. The inside surface of such a cone is covered with a paste, composed of the salt rubbed down in a mortar with picric acid, ammonia, and alcohol. The burner is adjusted at the focus of the condenser, and gives good bright spectra.

With the arc light the positive carbon or crater must be reversed so as to form the bottom pole, and a cup is formed in it, in which a morsel of the metal is placed. The poles must stand vertically, and a Brockie lamp will therefore require a wedge-shaped piece of wood placed under its base. A hand rack-regulator is however most convenient for mere spectrum-work.

85. **Reversed Lines.**—In 1859 Kirchhoff cleared up the mystery of the solar spectrum, by ascertaining that when the vapour of sodium was *interposed* between the slit and its spectrum, *the* D *line was still further darkened.* We have seen the bright D line of sodium, as projected from the lantern. We now restore the lime cylinder to its place, and throw the continuous spectrum on the screen in the ordinary way,[1] with a good prism bottle. At the point where the rays from the slit are made to cross by the lens, adjust the Bunsen burner, and

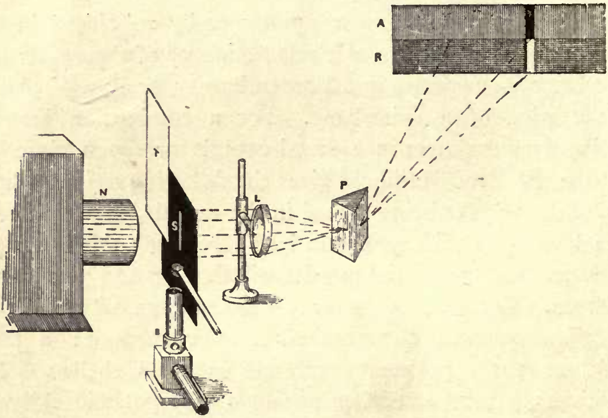

FIG. 93.—Reversed Sodium Line.

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[1] Nothing less than the mixed jet is brilliant enough to show the reversed line on the screen.

between the burner and the screen interpose a black card, so as to stop all *direct* light from the sodium from falling on the screen—hence a direct prism is not well adapted for this experiment. A little in front of the flame the prism is placed. Thus the sodium flame is not concentrated or focused on the screen at all, while all its direct light is easily shaded.[1] Introducing a pellet of sodium into the flame, it bursts into vivid combustion, and the light from the slit has to pass through the yellow flame. At once a *dark band in the yellow* appears on the screen (E, Plate II). It is not really black; for we know that if the sodium flame alone were employed it would give the yellow band; but it is *comparatively* dark: it stops the larger portion of the brilliant light from the lime cylinder. See also note to § 89.

With the arc-light we can show the two spectra together, and demonstrate that in this way we get an exact and absolute reversal of the sodium line. The arrangement is shown in Fig. 93. Everything but the condensers is removed from the lantern, and a few inches from the flange-nozzle, N, is adjusted a rather large black tin screen, S, in which the slit is cut, and which has side-guards (not shown) in order to stop as much as practicable scattered light. Behind the slit is arranged the Bunsen burner, B; by this arrangement all the light has to pass through the sodium flame, while none but what passes the slit can reach the screen. On now holding the spoon with the pellet of sodium in the flame, the dark band appears in the spectrum; and by holding another plate, T, between the Bunsen burner and the condensers, the arc-light may be cut off from the upper portion of the slit, leaving the light of the sodium flame alone. Two prism-bottles should be used, and the result will be as shown. One half of the spectrum will show the bright line on dark ground, giving the radiation

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[1] This arrangement, devised by Mr. E. Cleminshaw, is, as he states (*Proc. Physical Soc.* vii. 53) much easier than the one given by me in the first edition of this work, and superior in effect to it.

spectrum of sodium, R. The other half will show the dark line on the continuous spectrum, giving the absorption spectrum, A.

The mere dark-line spectrum is very readily shown with the arc-light, only needing a rather large and deep cup-carbon.

86. **Radiation and Absorption Reciprocal.**—After all, this is what we should have expected. It simply shows us that, as we have found reason to suppose before, the molecules of matter really do take up or absorb those ether-vibrations which *synchronize* with their own vibration-periods. We form the conclusion, subject to experimental verification, that all vapours ought to *absorb* the very same colours which they *radiate* or emit when heated to incandescence. Experiment does verify the conclusion. In every case, where the vapour of a metal gives out bright lines, there, when interposed in the path of a brilliant continuous spectrum, that spectrum is crossed by dark lines.

87. **Fraunhofer's Lines.**—We can now perfectly understand the solar spectrum (Plate II. D). The dark sodium or D lines show us, that between the incandescent body of the sun and ourselves is the vapour of sodium; other lines demonstrate the presence of incandescent hydrogen; other lines, again, those of iron. With greater dispersion the dark lines are, as already observed, multiplied to hundreds, and nearly a hundred of these are iron lines.

Fraunhofer's lines are of great value in another way. They serve as *land-marks in the spectrum.* It is difficult or impossible to determine light of a given wave-length by the colour alone; but these lines have fixed places, and, being all carefully mapped, answer every purpose (§ 81). Where no solar spectrum can be employed, still the ascertained lines of iron, or sodium, &c., answer the purpose, the chief lines being all lettered and numbered.

88. **Reversed Solar Lines.**—All the preceding suppositions can be actually verified in the case of the sun, and we

are able to obtain, with proper instruments, just such reversed or complementary spectra as our lantern gave us of the sodium line. If the sun is surrounded by various incandescent vapours, and these could be isolated from his overpowering continuous spectrum, we must have the *bright* lines. This was first accomplished during total eclipses, when the incandescent atmosphere gave the bright lines of sodium, hydrogen, iron, and other substances, conspicuously enough. By wider dispersion, which it will easily be understood weakens proportionately the continuous spectrum, while not able so to disperse the more definite vibrations of line spectra, spectroscopists are able to show in juxtaposition the spectrum of the sun himself, and of his outer envelope of luminous gas, or chromosphere. Fig. 94 shows a very small portion of the result,[1] and we see plainly the *bright* F line in the chromosphere, while below is the portion of the continuous spectrum, which shows the *dark* line exactly coincident, just like the two sodium spectra in Fig. 93

FIG. 94.—Solar F Line Reversed.

89. **Thickened Lines.**—There is one more rather important point. We have seen that solids or liquids, whose molecules are comparatively close, when those molecules are forced into violent vibration by heat, appear so hampered as

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[1] Taken from *The Spectroscope* (*Nature* Series).

to vibrate in all periods, thus giving the continuous spectrum. When the molecules are at last driven apart, and are comparatively free, they vibrate in their own individual periods, and give lines—at least this is our hypothesis regarding the phenomena. If it be well founded, we can test it; for obviously more pressure, or compressing even gas particles closer together, ought to produce more or less *approach* towards a continuous spectrum. Experiment verifies this, and many gases have been so compressed as to give a very considerable spectrum. The easiest demonstration, however, is with our ever-useful sodium and its reciprocal absorption spectrum. Enclosing some fragments of sodium in an exhausted tube afterwards filled with hydrogen, and again exhausted before sealing (this is to prevent oxidation), we have the materials for a very elegant experiment.[1] We throw the line spectrum on the screen as before, and hold the tube over the slit—there is no appearance of absorption. Applying heat, a *thin* dark line comes on the spectrum, which we know so well. Continuing to apply heat, we of course increase the density of the sodium vapour, and its pressure; and as we do so the line *thickens*, till it occupies a rather conspicuous width. Removing the lamp, the phenomena are all reversed. Our theory, and the expectations formed from it, are verified to the minutest particular.

Again, referring to Fig. 94, it will be seen that the bright F line of the sun's chromosphere is much *thicker* at the bottom than the top. We gather from this optical evidence, what we know must be the case on other grounds, that the pressure of the incandescent atmosphere is much greater near the sun's surface.

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[1] Due to Dr. Frankland. There is some little risk about this experiment, unless carefully prepared with strong and hard combustion-tube, which, should not exceed about $\frac{5}{8}$ inch in diameter. Heated to a less extent, the tube will be found to cast a shadow in the orange rays of the spectrum, but not elsewhere.

90. **Solar and Stellar Chemistry.**—Thus we see how the spectrum enables us to ascertain with wonderful accuracy much about the actual components, and even actual physical condition, of the most distant heavenly bodies. It is interesting to find that, so far as we can trace them in our telescopes, these are constituted of precisely similar matter to what we are familiar with, governed by precisely the same laws. Diverse and inconceivably far apart—far enough for even Light, with its enormous velocity, to occupy hundreds of years in traversing the distance—all are yet one vast unity. We can trace their materials, and sort them out into groups according to their stages of development; we can tell if they are solid, or gaseous, and whether they have a surrounding atmosphere or not. Though so distant that the most precise measurements fail us, if they are rapidly approaching or receding from us we can know the fact (§ 81). The Light they send us is a true Revealer of all, and brings evidence of all these things in its beams.

CHAPTER VIII

PHOSPHORESCENCE.—FLUORESCENCE.—CALORESCENCE

Effects of Absorbed Vibrations—The Invisible Rays of the Spectrum—Three Independent Spectra non-existent—Phosphorescence—Fluorescence—Calorescence—Relation of Fluorescence to Phosphorescence.

91. **Effects of Absorbed Vibrations.**—In previous chapters, we have been led to adopt as our hypothesis of absorption, and of the cause of colour in coloured substances, that molecules of matter having certain periods of vibration, took up from ether-vibrations of all periods, such vibrations as synchronized with their own, with others in less degree. We are bound to ask, what becomes of these absorbed vibrations? Energy cannot be annihilated; and any motion apparently destroyed must produce certain effects. If molecules of matter take up vibrations from the ether, these molecules ought, in their turn, being set vibrating, to give out new light, or at least waves of their own. That this is so as regards heat and light, is beautifully shown by the allied phenomena of Fluorescence and Phosphorescence.

It readily appears, on reflection, that when small particles (as of the Ether) act by their motions upon large particles (as of Matter), the more common effect must be the conversion of quicker motions into slower ones. To use and expand a dynamical analogy which has been employed by Professor Stokes, let us consider short and choppy waves acting upon a large vessel anchored at sea. The quicker motions cause a *slower* pitching and rolling of the vessel; and these, again, originate new and *slower* waves in the water. But the latter are less perceptible than the primary waves, and may even be unnoticed, unless the water should become suddenly calm; when they would at once be conspicuous as long as the rolling continued, a period which would depend on the stability of the vessel. In the same way, long slow waves may more rarely be converted into quicker motion, and thence into *quicker* secondary waves. Regard the waves as motions of ether atoms, and the vessel as a molecule of matter, and the analogy is fairly complete.

92. **Invisible Parts of the Spectrum.**—But before we can fairly investigate these matters, we must take into our view more than the spectrum we "see" upon the screen. That spectrum has no sharply-cut ends; and we know well enough that it has other effects than visual ones. We can readily trace *heat* in it; and experiment in even a very rough way with a good thermometer, soon shows us that the heat is much the greatest at the red end. If, on the other hand, we expose a photographic plate in the spectrum, we find very energetic *chemical* effects; and as regards salts of silver and many other compounds, we find that the power of producing such chemical changes is much more energetic at the violet end.

If we push our experiments farther, with more delicate instruments, we find that some of the most energetic heat rays are quite *outside* of the visible red end, in a dark space, representing still slower vibrations than the slowest red waves. And we also find that some of the most energetic chemical effects are produced in an invisible region *outside* of the visible violet end. Moreover there are broad absorption bands and Fraunhofer lines in these invisible regions; and there are bodies, alike in being perfectly clear and transparent to "visible" light, which differ widely in transparency as to these invisible rays. Clear rock-salt is the only body transparent to all the heat rays: and quartz is one of the most transparent to the chemical rays, which are largely absorbed by glass; as the heat rays are almost totally stopped or absorbed by solid alum or water.

93. **Three Independent Spectra non-existent.**—Hence diagrams have been constructed showing the comparative intensity or working power of what is called the Light spectrum, the Heat spectrum, and the Chemical or Actinic spectrum; the energy of each in every region of the spectrum being shown by a curve, whose highest point is at the place in the spectrum where the effect is greatest. Thus, the highest luminous intensity would be over the yellow. And it was once considered that there were in a beam—say of sun-light—rays of *three distinct kinds*, called heat rays, light rays, and actinic or chemical rays.

But this is now known to be a mistake. All the rays are subject to the same laws, being reflected, refracted, diffracted, &c., exactly as the rays whose luminous phenomena we have investigated. They differ solely in their *periods of vibration;* and their different effects are due simply to the fact that certain periods and lengths are best adapted to produce those effects. Just as with sounds, some persons can hear much graver sounds and others more acute sounds than others can, and probably insects can hear sounds inaudible to us; so while the lengths of average *visible* light-waves range only from $\frac{1}{36000}$th to $\frac{1}{62000}$th of an inch in air, some persons can see rays at one end or the other, invisible to the majority. Again, it has been said that chemical effects are almost *nil* in the yellow of the spectrum; and it is so as regards the salts of silver. But the action of light upon plants is also a distinctly chemical effect; and this is perhaps, if anything, the most powerful in that same yellow region. Science knows *no real distinction but periods and lengths*, between any of the rays in the spectrum; each period being more or less adapted, as a rate of Motion, to produce certain effects upon the molecules of bodies, or upon our nerves.

Now as respects such effects, we have a proof that the quickest motions act most powerfully in some respects upon the molecules of matter, in the effects of vibration upon wrought iron. Slow motions do not affect it; but quicker vibrations rapidly produce a crystalline structure, showing that the molecules are shaken, or forced in some way, into new positions. We see practically the same thing in the chemical power of the quicker waves of light. It is almost certain that the atoms upon which they act, are literally shaken into new combinations, very much as in the crystalline iron; and thus we can imagine *why* it is that the quickest vibrations are often most powerful in their effects. Actinism is thus, in itself, one of the strongest proofs of the vibratory theory of light. As the transference of motion we here suppose, is from the ether to the ponderable atoms of bodies, we should expect to find it in some respects most evident from the quickest waves.

We thus see, in a general way, what becomes of light when it meets bodies opaque to any given periods of vibration. It can always be traced somewhere. It is largely converted into heat in the body, while many reflected vibrations which would be true visible waves as regards period, are simply too weak to be discerned. We should *expect* that the quicker motions would be, as a rule, most readily traced; and again, as a general rule, converted into slower ones. And yet we ought to find some exceptions to this rule, and many proofs in one way or another of what we are supposing takes place.

94. **Phosphorescence.**—It will thus be understood, that when we place a body in the sun for some time, and on removing it, find that for a considerable time it gives out perceptible heat rays, we have a case of what has been here described. Some people's eyes are sensitive to light much more faint than others can perceive: and if a large iron ball is heated white-hot, and then gradually cooled, such individuals may see the red light after others have ceased to perceive any visual phenomena. Hence there can be little or no doubt, that in the

case of a body merely "warmed" in the sun's rays, there are also vibrations of shorter, truly visual periods, but too feeble for our senses. But there are a number of substances which, when exposed to light for a time, continue for some time after withdrawal to give out *luminous* rays, and this phenomenon is called *phosphorescence.* Prominent amongst these substances are the sulphides of calcium, strontium, and barium; but they require to be heated and hermetically sealed in glass tubes. The diamond and fluor spar are examples in the mineral world. The compound sold as Balmain's luminous paint is one of the cheapest and best-known substances. Diamond and fluor spar glow for a comparatively short time after exposure to a strong light; but the sulphides, or Balmain's paint, will shine for many hours by the energetic vibrations set up in their molecules by the ether-waves.[1]

It is found that these effects are produced mainly, if not solely, by the quicker and shorter waves. If a sheet of paper painted with Balmain's paint is made slightly luminous, and then exposed in the dark to a strong spectrum for a while, when it is taken into a dark room it is found the phosphorescence is *destroyed* where the slower waves fell. Those waves have the property of destroying the vibrations set up by the quicker waves, converting them into slower, or heat waves.

95. **Fluorescence.**—But there is another class of bodies which are acted upon in a somewhat similar and yet somewhat different manner. The vibrations of the infinitely small ether-atoms set up in their heavier molecules *slower* vibrations, as in the case of our ship (§ 91.) We have had one example of this when light-rays are absorbed and cause heat-rays to be emitted from the body; but similarly, the very quick and short invisible violet rays may be converted into slower *visible* rays. Professor Stokes found that when he employed quartz lenses and prisms (§ 92), the invisible spectrum at the violet end was

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[1] A set of phosphorescent tubes, which give various colours after exposure to light, can be obtained for a few shillings of any good optician.

six times as long as the whole visible spectrum. It is no wonder, therefore, that this should be the most common of all these allied phenomena. It is called Fluorescence, and has been specially investigated by Professor Stokes, and since by Lommel, Kundt, and others.

The conversion of invisible rays into visible ones is not very well adapted for ordinary lantern arrangements, for two reasons: firstly, incandescent lime is not rich in the invisible violet waves;[1] and secondly, crown glass lenses, and still more bisulphide prisms, are powerful absorbents of them. The electric light is extremely rich in these rays, much more so than that of the sun. The most convenient light for ordinary lantern experiments is that of magnesium ribbon, also rich in violet rays; and it may be used without any special expense, by adjusting a bit of brass tube and passing through it two or three ribbons; one of the three will then keep the others alight, but the light must be watched through a bit of dark glass. The lantern itself and the spectrum are, however, only needed to show the creation or conversion of the invisible spectrum into visible rays; and this is easily done by adjusting a spectrum from a *glass* prism on the screen. We project the spectrum, stop off all the brighter portion, and pin over the violet end and beyond it, a white card painted with several coats of a solution of sulphate of quinine in water acidulated with sulphuric acid. We see a very obvious *brightening* of the visible violet, and that a perceptible region, before invisible, becomes visible where painted with the quinine (Fig. 95, B C). Taking a glass tank or large cell of the quinine solution, and interposing it in the path of the lantern-beam, the screen shows that it is as clear and colourless as water. But holding the cell so that the light *in* the cell can be seen, it glows with a beautiful bluish shimmer. A beautiful cone of blue light will be seen if we allow a large lens to come to a focus in the body of the tank.

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[1] The best actinic effects are from a magnesia cylinder.

With this cell we can show the perfect reciprocity between radiation and absorption which we have found before. We project from the lantern, with a flint-glass (in default of quartz) train, the ordinary spectrum, A, B (Fig. 95). Towards the violet end B, is attached the piece of white card painted with the acid solution of quinine, producing the brightening at B and extension to C. Now we interpose in front of the slit or lantern-nozzle the glass cell filled with quinine solution. The B C portion at once disappears, and the spectrum is brought back to its former dimensions and character. The demonstration is thus complete, that emission here also is reciprocal with absorption. We further perceive the reason why, in examining *cells* or *tubes* of quinine, a weak solution is better. In strong solutions the effect only penetrates to a small depth, because as the light penetrates, more and more of the effective rays are absorbed; until, at last, the light that has got through a certain amount, though to all appearance as white and complete in various waves as ever, has utterly lost all power of exciting the same kind of fluorescence. The exciting rays have been taken up by the quinine, which emits them on its own fresh account; and therefore they no longer exist to cause fluorescence in what quinine may be behind. This is, however, only true of the *same* fluorescence. While the fluorescence in a tank of quinine is quite stopped by another tank of quinine, if instead of the latter we interpose a tank of uranine or fluorescein, its green fluorescence does not stop the other,

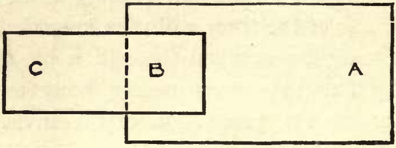

FIG. 95.

but both tanks will still glow brightly with their characteristic phenomena.

Having demonstrated the spectral relations of these or any other fluorescing rays, however, a more convenient plan is to burn magnesium in a small box with one side of violet glass. This glass, of course, has no operation beyond stopping off the more brilliant part of the spectrum, which might otherwise overpower the more feeble fluorescent effects. The private student may use sunlight admitted through a small square of blue or violet glass into a dark box. Or if an induction coil is at command, a vacuum-tube filled with rarefied nitrogen, or even air, gives a light feeble, but rich in actinic rays, which, if surrounded by a large tube in which fluid can be introduced, gives fine effects. The purply-blue light of burning sulphur is sufficient for many substances; and sulphur burning in oxygen, or some potash pyrotechnic mixtures, give powerful effects.

There are an immense number of fluorescing substances, amongst which many of the following were brought to my notice by Mr. Sidney Jewsbury of Manchester. The most powerful fluorescing colours in general appear to be green and greenish yellow, in either of which it is easy to prepare designs (best upon darkish blue paper or card) which will shine out brilliantly in light which has passed through blue glass even from the ordinary lantern, or in cells of solution will glow magnificently in the rays from even an oil lamp. Designs are executed in warm size made from gelatine, in which the dye is dissolved, and which is laid on thickly with a brush, so as to give an appreciable thickness on the paper of fluorescent material; or sheets of gelatine may be soaked in the dye, and when dried, geometrical shapes may be cut out from it and caused to adhere to a card. Fluorescein fluoresces a brilliant bright green. Its sodium compound uranine is a magnificent lighter green. Fused with bromine it gives eosin, also green. Chrysoline is a very pure green. All the above are red or yellow in solution; and besides the above treatment, if a clear glass jar of water containing a few drops of ammonia be placed in the path of the lantern beam, and about a grain in powder of either of the above be scattered on the surface, exquisitely beautiful arborescent streams of green reflected light will be visible. Almost any red ink, even, dropped from the tip of a pen-holder into water, will exhibit the same phenomena, most of these inks being made from eosin.

Barium platino-cyanide is another brilliant substance fluorescing a yellow-green, but is best rubbed up with gum water. The most brilliant of all is probably a substance extracted from petroleum residue by Professor Morton, and termed by him thallene. I have not been able to find any medium which dissolves it (water, alcohol, ether, benzol, were all tried in vain), and Professor Morton, in kindly sending me a sample, told me he preferred to rub it up like paint with thin dammar and benzol. It is found that many carbon compounds containing slight and unknown impurities possess a brilliant fluorescence, which they lose when purified; and accidental samples now and then occur in this way which cannot be duplicated. Glass coloured with uranium oxide is another substance fluorescing a brilliant green, if cubes or vases made of it be placed in the lantern beam which has passed through blue glass.

Powerful fluorescence of other colours can be obtained in a tank of solution, making the latter weak enough for the cone of light to be clearly marked; but I have not found it possible as yet to get much effect from any of them as regards designs upon paper. For blue, quinine has already been mentioned. Æsculin fluoresces a bright blue in slightly ammoniated water, and streams of fluorescent light will descend from even small bruised fragments of horse-chestnut bark thrown on the surface. Most petroleum oils fluoresce blue, and so do sodium compounds of the β naphthol sulphonic acids. Cyanosine (or methyl-tetraiodo-fluorescein) fluoresces orange in alcohol; and so do some of the rhodomines (water), the solution being crimson. Magdala-red fluoresces orange-red. Diazo-resorufin dissolved very sparingly in methylated alcohol slightly ammoniated, fluoresces a vermilion red, but is itself red in solution. The tetra-bromide of the same is however blue in solution, but also fluoresces red, though a more dull red than the other. A solution of chlorophyll (or extract of nettle, or almost any other green leaves in alcohol, ether, or benzol) is green in solution, and fluoresces a dull blood-red. If we place a cell of chlorophyll before a slit in the lantern, and throw its absorption spectrum on the screen (Plate II. G) we can trace again the reciprocity of radiation and absorption —for taking a *dark* absorption band, we find the fluorescence is *brighter* in those particular rays.

As illustrating the wide range of these phenomena, a simple experiment described by Professor Stokes, though only adapted for private performance, is very suggestive. Darken a chamber or box, except a small window of dark blue glass, such as transmits through a window, when analyzed by a prism, only the violet, blue, extreme red, and perhaps a little green, but the less green the better. In the fullest light of this blue window lay a white plate or tile ; of course, on laying over this a slit cut in blackened metal or card, we see the same spectrum, only fainter. But now again we lay on the white a bit of bright scarlet flannel or cloth, so that through half the slit we see the white plate, and through the other half the scarlet, and can thus compare the spectra on again looking through the prism. We naturally expect the blue and violet part of the cloth spectrum to be nearly black, as it is, in the violet light ; but what the student probably does *not* expect, but what we shall find with many samples of scarlet, is to see the spectrum of the cloth *lengthened towards the red end*, and altogether more brilliant in the red portions than that of the white plate.

In the majority of fluorescent substances shorter waves produce vibrations of slower period, or lower refrangibility, and hence the difficulty of exciting blue fluorescence especially, through lenses which powerfully absorb the ultra-violet rays. But such is not always the case. The orange-red fluorescence of naphthalin-red is excited more or less by nearly all the rays except the extreme red; and fluorescein and its allies (eosin, uranine, &c.) shows its green fluorescence in nearly all the rays, shining even in gas-light. Here, therefore, we have a distinct proof of fluorescence being set up by waves shorter than those of the fluorescent colour produced.

96. **Calorescence.**—Still further, as Professor Tyndall has shown, we can stop off all but the slowest waves—all but the *invisible* heat-rays—by passing the electric beam through a cell filled with iodine dissolved in carbon bisulphide. If now a large quantity of these invisible or slowest waves be condensed upon platinum foil, or other suitable substances, they will produce either a red, or even a white heat, thus causing the substance to give out also the *quicker* waves of the spectrum.[1] Here again is a rise, or exaltation of refrangibility, or the conversion of slow vibrations into quicker ones. This phenomenon Professor Tyndall has called *Calorescence.* It is the reverse of what occurs when absorbed light produces heat (§ 93).

Thus we have found all our expectations exactly fulfilled. As a rule, the quickest waves are most noticeable in their effects; and, as a rule, the extra-violet and violet waves are converted into slower waves, the extra-violet becoming

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[1] Carbon bisulphide is dangerous to use; but the experiment may be performed quite safely by substituting carbon tetra-chloride. The solution in this liquid is not absolutely opaque, but only a little violet struggles through, which is hardly perceptible. Using a mixed jet of $\frac{1}{10}$ inch bore with high pressure, the whole lime will become incandescent, and radiate great heat if of the hardest Nottingham kind. All lenses should be removed, and a thin spherical glass flask filled with the solution be placed about six inches from the lime. If a bright tinned or silvered tube to slide in the flange nozzle occupy the intervening space, it will still further concentrate the heat upon the flask, which will act as a lens, in whose focus the paper or foil is to be placed.

violet, or blue, or green, and the violet a brighter blue, and so on. And yet we have a few examples of the reverse in naphthalin red and a few other substances. And yet, again, we have in phosphorescent substances examples of matter-molecules set in vibration by the ether-atoms so vigorously, that they give out light for a considerable time. The probability is that *all* or nearly all substances fluoresce and phosphoresce, but that in most cases the vibrations are too feeble to excite in our eyes visual effects.

97. **Relation of Fluorescence to Phosphorescence.**—It needs one more step to make the analogy complete. Phosphorescence, as shown by Balmain's paint, ought to be clearly connected with fluorescence. This step was always felt to be necessary by Becquerel, and it was he who accomplished it. To ordinary observation, the effects of fluorescence seem to cease immediately the exciting light is withdrawn, while phosphorescence lasts perhaps for hours. Becquerel, however, constructed a "Phosphoroscope," by which the illuminated fluorescent substances could be rapidly removed from the light, and he thus found they retained luminosity for a calculable time. His instrument is rather complicated; but Professor Tyndall, whose fertility as an experimenter is well known, in his lectures at the Royal Institution, used an apparatus much simpler and more elegant. A square iron lantern, A (shown in plan in Fig. 96), had on one side a slit B, through which alone the light could pass. Dr. Tyndall, of course, used the electric arc; but magnesium will do nearly as well—anyway, we represent the light at C. Outside the slit, which is of course vertical and nearly the depth of the lantern, is mounted on a per-

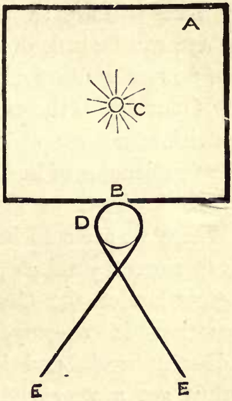

FIG. 96.

pendicular axis the cylinder, D, driven by a grooved pulley and cords, E E, from a double system of multiplying wheels, so as to give swift rotation. This cylinder is painted with uranium or canary-glass, powdered, and the powder laid on as paint with some transparent vehicle. Turning the slit and cylinder towards the observer, it will be obvious that if there were no duration of luminosity, or true "phosphorescence," in the case of the fluorescent cylinder, it must appear dark; but on imparting rotation, it shines brilliantly with the characteristic green light. Some of the powerful fluorescent dyes already mentioned give the same phenomena. Thus, then, fluorescence is linked on to phosphorescence; and though all fluorescent substances will not show this with ordinary experimental means, there can be little doubt that it is only a question of degree, and of powers of observation.

Once again, therefore, Light has revealed to us the minute, invisible motions which its own ether-vibrations communicate to the molecules of bodies. Where we may have thought all was still, it shows us molecules in constant and rapid motion. Where we seem to have lost that motion, further reflection and experiment yield us but another and impressive proof of the great law of the Conservation of Energy. We see that no motion is destroyed; but that every single movement does its work, and is converted into some other form. We thus get a very vivid idea of the intense *reality* of these motions, which seem hypothetical only because they elude the direct examination of our senses. That sense of their reality and definiteness will help us to understand the beautiful and new field of experiment, embracing the most splendid phenomena of physical optics, which we now have to investigate.

CHAPTER IX

INTERFERENCE

Net Result of Two Different Forces—Liquid and Tidal Waves—Why Single Interferences are not Traceable in Light—Interference of Sound Waves—Thin Films of Turpentine, Transparent Oxide, Soap, Water, and Air—Colour Dependent on Thickness of the Film—Newton's Rings—Proved to be Dependent also on Reflection from both Surfaces—Spectrum Analysis of Films—Phenomena of Thicker Films—Soap-Films and Sound Vibrations—Colours of Thick Plates—Fresnel's Mirrors — Fresnel's Prism — Irregular Refraction—Diffraction—Gratings—Telescopic Effects—Other Simple Experiments in Diffraction—Striated Surfaces—Barton's Buttons—The Diffraction Spectrum—Measurement of Waves—Change of Phase in Reflection from a Rarer Medium — Photographic Demonstrations of Interference — Hertz's Experiments—The Size of Molecules of Matter—Appendix on Diffraction in the Microscope.

98. **Net Result of Two Different Forces or Motions.**—We have now to study a class of experiments which most of all clearly demonstrate the wave character of the phenomena which constitute Light. We know that different separate motions can so act upon the same particle of matter, as either to combine and strengthen, or to neutralize and destroy each other; because the actual motion of any particle must result from the net sum, difference, or other result of the forces which act upon it. Take a billiard ball travelling in a direction and at a rate resulting from some stroke of the cue;

if we impart another impulse in the same direction the velocity will be increased; while if the ball be met by a second force of the same amount, it is brought to a standstill.

99. **Interference of Liquid Waves.**—The same must result in the case of any *series* of vibrations of equal amplitudes

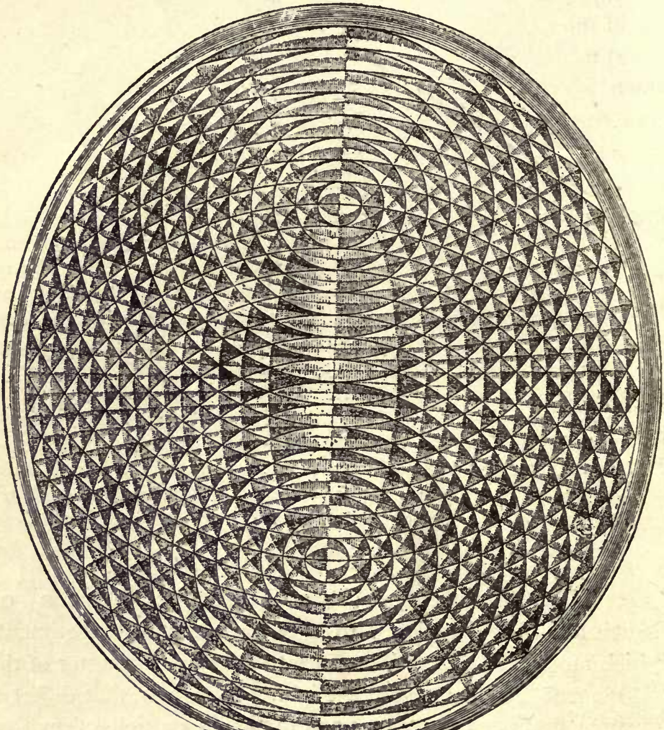

FIG. 97.—Interference of Liquid Waves.

and periods, such as constitute a wave. If we drop two stones at some distance apart into the same pond, the circular waves from one will cross those from the other. At some points the crests will coincide, and reinforce each other's upward movements; at others the same particle of water is elevated by one wave and depressed by the other; there it is at rest. The consequence is a beautiful pattern caused by the intersecting ripples. Fig. 97 shows such a pattern caused in an elliptical bath of mercury by a drop or point introduced at one of the foci. They can be shown by the vertical attachment (§ 12) to the lantern, laying over the condenser a glass plate to which is cemented an elliptical tin wall, making a tank some 6 inches in diameter and an inch deep, with a glass bottom. On focusing the surface, and then exciting waves by the point of a rapidly vibrating wire, the intersections of the original and reflected waves will be depicted upon the screen.

100. **Interference of Tidal Waves.**—The same thing is true of tidal waves, a remarkable example of which is found in the channel between England and Ireland. The flood-tide, sweeping round from the Atlantic to the north and south of Ireland, meets about a line which usually passes just across the south of the Isle of Man. There the two *currents* destroy one another, and there is practically none, while the rise and fall of the tide is greatest. But going back from this point to north and south, there are also two points (near Portrush, in Antrim, at the north of the Irish Channel; and near Courtown, in Wexford, at the south) where the falling tide meets the next rising tide; at these points, therefore, there is practically no rise or fall of tide whatever, while the *current* is at the maximum. The same is true of the vast tidal waves that sweep round the globe. At certain times the sun-wave coincides with the moon-wave, and then we have the greatest tidal motion; at others the sun's wave opposes the moon's wave, and we have the least motion.

101. **Single Interferences not Traceable in Light and Sound.**—But here we must make a very important distinction, the want of which has caused many a student difficulty. In the foregoing cases we could trace the interferences of *single*

waves, because their motions were large, occupied considerable time, and thus enabled us to trace them—most clearly in the grand tidal waves, which are longest of all. The student is apt to fancy that, in a similar way, rays from any two points of light must be constantly destroying one another by interference, much as in Fig. 98, supposed to represent the rays from two lighthouses. And to some extent they undoubtedly do so. But they can only thus act on each other at the *points* where the undulations cross; and in the case of light the vibrations are so enormously rapid and numerous, that the comparatively few extinctions of this kind are not sensibly missed.

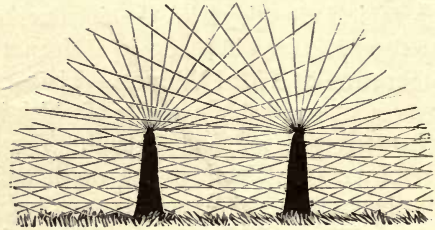

FIG. 98.—Two Lighthouses.

But if we bring a whole *wave series* to act upon another similar whole wave series, then any effect at one point in any waves of the series is repeated throughout the series, and the effect becomes visible. In the case of sound we can get similar wave series easily, by employing exact unisons; and so it will be found, if a tuning-fork be struck and held close to the ear, that on turning it round on the stem there is a position in which the sound is nearly or quite extinguished. This position differs, as it should do, with the key of the fork; but is when the two prongs are at an angle of nearly 45° with the direction of the ear. If the fork is steadily rotated, the sound will be alternately extinguished and reinforced, according to the phases in which the waves from each prong encounter one another.

In the case of light, as a rule, we can only get the exact similarity necessary, by employing two portions of light from the same original point of emission, or very nearly so; but if we can bring two such exactly similar series of waves again together, or so *close* together that the ether-atoms set in motion by them can act upon each other, while the paths of the rays are sufficiently parallel for many successive undulations to come into the same relations, then we ought to get effects which shall be visible to us. There are several methods of effecting this object.

102. **Colours of Thin Films.**—The simplest and one of the most striking is reflection from a "thin film." If a pencil of light A (Fig. 99) strikes any thin transparent film at B, we know that a large part is reflected at a similar angle to C. But the rest is refracted to D, where (unless at the angle of total reflection) a portion passes through and is lost to us, while another portion is reflected to E and thence refracted to F. It is evident the ray E F must be precisely similar to the ray B C in the periods of its waves, and also precisely *parallel* to it; and, if the film be thin enough, it should also be *near* enough to it to cause interference.

As to the phenomena we ought to expect, remembering that every colour has its own wave-length, and reverting to the wave-slide shown in Fig. 78, we see there how the retardation of the central section of that slide by a given distance brings the long waves into contrary phases, while the short waves of half the length, at the same time exactly coincide. A very little thought will teach us that with waves of all various lengths, only *one* length can be *exactly* coincident, and only one *exactly* contrary in phase, when one set is retarded a given distance; all others being affected one way or the other in varying degrees. Applying this to colours, and remembering what we have found already as to the effect of suppressing any part of the spectrum, we therefore expect that *colour* will be produced.

Now in Fig. 99 this state of things is what we have. The ray E F has had to traverse the film twice, from B to D and from D to E, before it can start on its journey parallel to B C. It has got by that distance *behind* B C, and as this retardation affects each length differently, and more or less suppresses some lengths while it more or less strengthens others, we are prepared to expect colour, if the film is thin enough to allow the two to act upon each other at all. We can subject the matter to experiment in many ways, all of which give phenomena of great beauty.

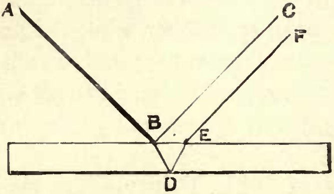

FIG. 99.—Reflections from a Film

Take a small black tray or hand-waiter W, say 8 by 12 inches, lay it on the table, or on a block to raise it if needful, and fill it about half an inch deep with water. If it is a lime-light, cant up the back of the lantern, as in Fig. 100, so that

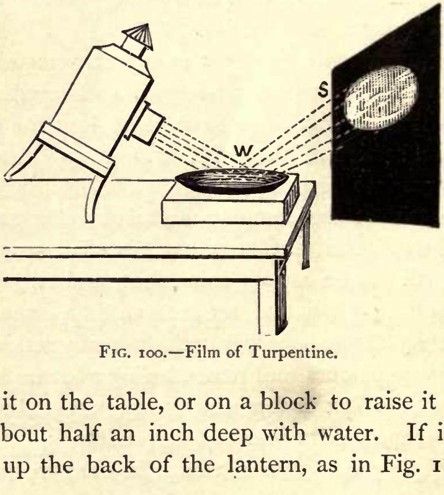

FIG. 100.—Film of Turpentine.

the parallel (or rather slightly divergent) beam from the flange-nozzle with the objective removed may fall on the water at W, and be reflected to the screen S. If it is a gas-burner, the reflector must be used to bring the beam down; and in some situations it will be best to *focus* the surface on the ceiling, as in some previous experiments; but with the lime-light the plain beam is best. Having adjusted all, dip the end of a pen-holder or any pointed rod into a bottle of spirits of turpentine, and let a single drop fall on the water. It spreads out instantly, and the reflected light on the ceiling or screen is tinged with the most beautiful colours.

Support a polished steel plate 3 or 4 inches square on a small tripod, and place a spirit-lamp or Bunsen flame underneath the centre (Fig. 101). Bring down the light from the lantern, and focus, as in Fig. 31; then light the lamp. As a film of transparent oxide forms on the steel, colour appears, which gradually takes the rough shape of variously coloured rings, though not very regular. This experiment is a little tedious; but it is a very interesting one. Oxidation may be hastened by covering the hot plate with a very thin film of paraffin-wax.


FIG. 101.—Film of Oxide.

103. **Soap-Films.**—Soap-films, however, offer the most splendid phenomena. A good solution is of great importance, and there are many recipes, the most generally known being Plateau's. For this dissolve 1 ounce oleate of soda, cut into thin slices, in two pints (40 ounces) *distilled* water, rather hot. Mix the solution with 30 fluid ounces of *pure* glycerine, and shake violently for several minutes, several times, with some hours interval between; then leave for several days before use (as the solution "tempers" together for a certain time), and filter clear on a cold day. This recipe does well for *warm* weather; but I think it toughens the solution to substitute for a portion

of the pure oleate, which should be fresh-made and soft, some shavings of Marseilles soap. Warm this at convenient intervals on the hob, or otherwise, for several days, shaking it and leaving it to settle between. Finally, let it thoroughly cool, add a few drops of ammonia, and then filter it at about 50° through Swedish paper into stoppered bottles, which will filter out all precipitate and make it clear. If, however, the weather turns very cold, or after considerable time, it may become turbid and useless; and it is necessary either to filter again, or (what does as well in the former case) to warm the solution before use, warming also the saucer and other apparatus. After all, the first solution thus made may not be thoroughly satisfactory. I then provide a number of such paraffined rings as are described presently, take small samples of the above "stock," and add to them separately (making memoranda) different quantities of soap solution, or glycerine, or water, well shaking and leaving them some hours to "temper"; then stretch a film of each on the rings, the ends of which are stuck into horizontal bradawl-holes in a long slip of wood. Notice is taken, comparing several trials, which lasts the longest; and when that is ascertained, the whole solution is made up to that standard. By this tentative method tougher solutions may be got than by any one recipe that can be given for a variable climate,[1] and with the varying qualities of soap, glycerine, and

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[1] Two other recipes may however be useful. The following is that adopted and recommended by Professors Reinold and Rücker and C. V. Boys. Fill a stoppered bottle three-fourths full with distilled water, add one-fortieth by weight fresh oleate of soda, and leave for a day to dissolve. Nearly fill the bottle with Price's glycerine, and shake well (it will be noticed that this is considerably less glycerine than Plateau's). Leave the bottle a week in a dark place, then with a siphon draw off the clear liquid from under the scum into a clean bottle, add a drop or two of strong liquid ammonia to each pint, and keep carefully in the stoppered bottle in a dark place, filling a small working bottle from it when required, but keeping the stock bottle undisturbed, and never putting any back into it. They advise never to warm or filter the solution, and never to leave the stopper out or the liquid exposed to the air. Herr Dähne, of Dresden, has a handy

even oleate. It is perfectly easy to place on the ring-stands shortly described, bubbles nearly a foot in diameter; and I have several times blown in the usual way globes *half a yard* in diameter; but even a twelve-inch is a magnificent object. A solution must always be brilliantly *clear* to do good work, and if turbid, should be re-filtered through Swedish paper before any important experiments. The saucer used must also be perfectly clean.

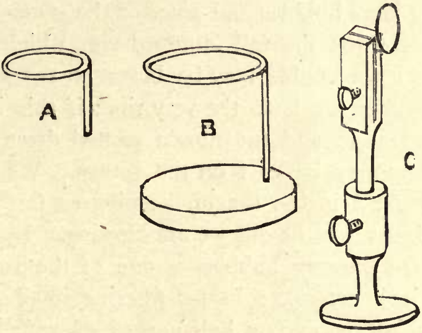

FIG. 102.—Rings for Soap Solution.

Make a few rings of 1-16 inch iron wire, like A (Fig. 102), 2½ inches diameter, and a few rather larger, say 3 inches: the

method, which allows the solution to be mixed as required, even in a test-tube, from separate ingredients kept in stock. Keep in bottles (1) a *saturated* solution of soda oleate in distilled water, carefully neutralised and filtered clear in the cold. (2) Filtered distilled water. (3) Price's best glycerine, tested free from acid. Then mix as follows, according to the purpose in view :—(*a*) For greatest *toughness* or lasting properties take one vol. oleate solution, one vol. glycerine, and two vols. distilled water. (*b*) For beautiful coloured bands, quickly developing : one vol. oleate, ¼ vol. glycerine, and four vols. water. (*c*) For rapid development of the black spot : one vol. oleate, five vols. water, and only a trace of glycerine. For a sudden emergency a simple solution of any good glycerine soap generally answers tolerably well. A solution may often be toughened for immediate use by a trace of gelatine ; but as the animal matter soon decomposes, such a solution cannot be preserved for any time.

latter stick into wooden feet as at B. Solder the joints, afterwards smoothing them off, and then dip the rings into melted paraffin, or warm them and smear very thinly with it, which keeps them from cutting the films. Arrange several of the B stands in a row, first dipping their paraffined rings in a saucer of solution and wetting them thoroughly with it; then we can with a little practice blow large bubbles and place on the stands. Through the whole row throw the full lantern beam, which gives a fine effect. Or a large bubble may be blown on the saucer itself, first carefully soaping it to the very rim; if this is placed in front of the lantern and the nozzle canted down towards it, fine reflections may be cast on the screen. We must avoid carefully all *froth* in the saucer, keeping as free as possible from all bubbles but the one we are blowing. By far the best instrument for blowing bubbles is one of the smallest *glass funnels* (an inch across), sold for filtering small quantities of fluid, on which is sprung half a yard of sufficiently small india-rubber tubing.

But the finest experiment is with a flat film. Pinch one of the A rings (Fig. 102) as at C, in the clip, the ring standing *above* its stem,[1] and adjust it so that the plane of the ring is vertical, and stands the same height as the lantern nozzle. Turn off the lantern L (Fig. 103), parallel with the screen, then dip the ring in the saucer of solution, lift a film, and place it, as at A, at an angle of 45°, with the whole light concentrated on it, which will be reflected to the screen, or a slightly convergent beam from the condensers will be better still. Turn the clip-stand till the reflected light is central on the screen, and then adjust the loose focusing lens F to form an image. A glorious image it is, as band after band of interference colours travels up the oval image of the wire (the bands really move *down* the film as it becomes thinner, but the image is of

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[1] The film lasts much longer thus than if the stem is uppermost, owing to the thinnest portion being dependent from the smooth and unbroken circular wire.

course inverted), while every motion of the film from the least breath of air is pictured plainly (Plate III. C). Simple as it is, there is no more beautiful experiment than this (unless perhaps the following modification of it), and with a good solution the film may last for an hour.

The horizontal bands are obviously due to the gradual thinning of the film under the action of gravity; and if we blow a large bubble on the saucer and place a glass shade over it, the bands will appear quite as regularly upon that. If we could make the thinning of a flat film take place round a centre, we ought therefore to get circular rings; and we can do this easily by a magnificent modification of the experiment, devised I believe by Lord Rayleigh. We only need a slight air-blast, which is best obtained from an acoustic bellows, but the breath may with care be made to suffice. The film being arranged as before, a small glass nozzle (for which one of the glass fillers sold with stylographic pens answers excellently) is

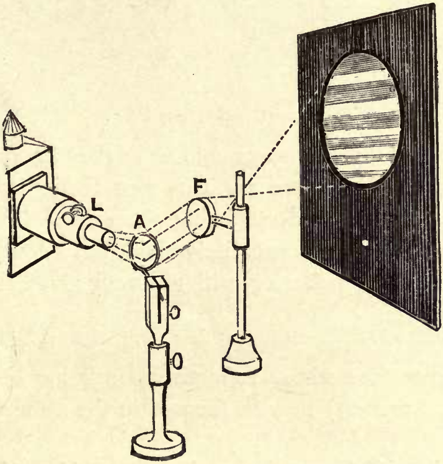

Fig. 103.—Projection of a Flat Soap-Film.

connected by a tube with the bellows (or the mouth) and adjusted in another Bunsen holder so as to direct a slight blast at a very small angle with the surface of the film. Adjusted as at A (Fig. 104), the whole is converted into one swiftly whirling vortex, which exhibits gorgeous colours as the film gets thinner. Adjusted nearer the centre as at B, two vortices will be produced, the chromatic effects being the same. The colours produced in this way are peculiarly vivid, but a tough solution is required, and a 2-inch ring will generally give better results than a larger size.

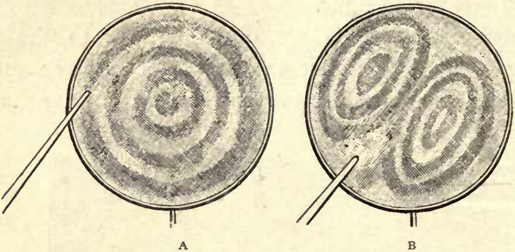

FIG. 104.—Rotating Soap-Films.

Any surface (not too convex) of iridescent glass (which has a film on the surface whose refractive power has been altered by a chemical process) may be focused in the same way as the soap-film.

Another beautiful experiment is with a film of moisture. Blacken a piece of glass on the back, rub a piece of soap over the surface, and clean off with a chamois leather. Pinch this in the clip, adjust it like the soap-film at 45°, and focus; but *keep it cool* by interposing a glass cell filled with water or alum solution, or the experiment will fail, as it depends on condensation of the breath by the cold surface. Then blow on the centre through an india-rubber tube of $\frac{1}{2}$-inch bore. As the breath condenses, roughly circular coloured rings will form, and gradually change as the moisture evaporates.

Next we may take a film of air. Get two squares of *plate* glass, say 3 inches square, and grind off the sharp edges to prevent scratching. Carefully clean them, and then carefully slide or grind them with moderate pressure smoothly together. We very soon see beautiful fringes of gorgeous colour. When satisfactory, pinch one lower corner of the double plate in the clip, and the three others with loose wooden spring letter-clips. Focus as before : all will be reproduced on the screen, and as we further pinch anywhere, even with the finger and thumb, changes and movements of the colours will demonstrate that the particular colour wholly depends upon the thickness of the film.

104. **Thickness of the Film.—Newton's Rings.**—We want to know, if possible, however, what that thickness is, and the last experiment probably suggested to Newton his famous "rings." He placed a convex lens of very slight convexity, as in Fig. 105, in contact with a flat glass, against which

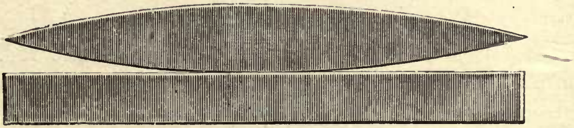

FIG. 105.—Newton's Rings.

it was pressed by screws. A simpler method sometimes employed is to cut two circular *flat* glasses (they must be a $\frac{1}{4}$-inch thick, or, at least, one must be so), and having carefully cleaned them, place a ring of thin tinfoil between them at their circumference. Mounted as in Fig. 106, pressure from the centre screw at the back produces, as in the other case, "Newton's rings," which, in either case, are presented to the lantern and focused on the screen precisely in the manner of the soap-film (Fig. 103). This method is within the power of many who like to construct their own apparatus.

It is clear that, knowing either the curve of the lens, or the thickness of the foil, we can calculate the thickness of the film of air at any given distance from the centre. Newton found that when he employed pure monochromatic light, he obtained *recurring* rings of coloured light, and of darkness, at once, twice, thrice, and other multiples of one definite small thickness. He soon discovered another beautiful fact, viz., that the rings were broader, or required a thicker film, in red light than in blue light ; and finally, by a movable prism, he threw the successive colours of the spectrum on the rings, and found them gradually contract as he travelled towards the violet end. With most lanterns there is hardly light enough to employ this beautiful method ; but the phenomena may be shown as follows :—Arrange the Newton's rings, and focus on the screen as before. Provide one of the movable slide-frames now used by all lantern lecturers, and fit in it two half-size glasses, one blue and one red. Condense the light on the rings ; and as close to them as possible, between them and the nozzle, hold the coloured glasses ; as these are moved from side to side, the rings will open or contract as the red or blue glass is interposed, and when they equally cover the rings, the two semicircular segments will be seen not to coincide, the red being larger in diameter than the blue. It is easy to understand, therefore, that if we employ white light, we must obtain rainbow-coloured circles.

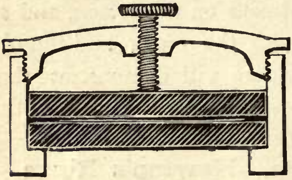

FIG. 106.—Newton's Rings with Flat Glasses

105. **Failure of the Emission Theory.**—Having to account for these phenomena, and adopting for practical purposes the corpuscular theory (§ 63) as his working hypothesis,[1] Newton accounted for his bright and dark rings recurring at

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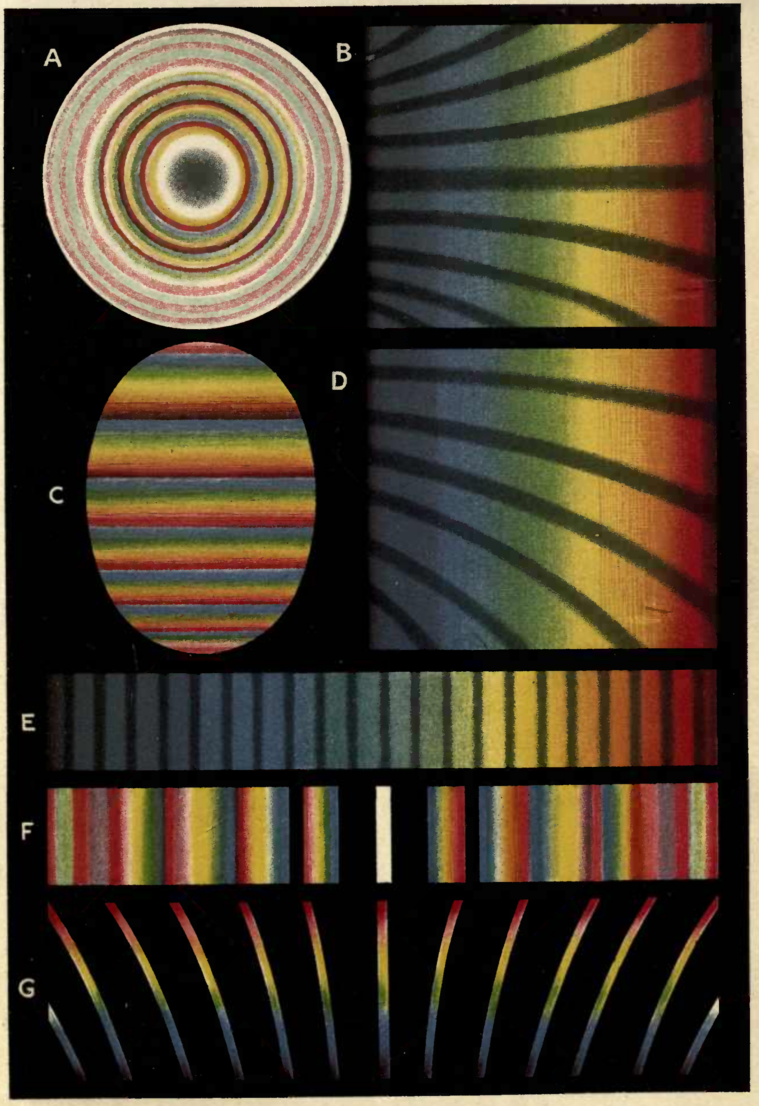
[1] There is ample evidence in the last edition of his *Optics*, that Newton was latterly very strongly attracted towards the Undulatory Theory, but did not feel justified in adopting it, owing to difficulties he was unable to solve.

Pl. 3.

INTERFERENCE



A. *Newton's Rings* B. *Spectrum of Ditto.*
C. *Soap Film* D. *Spectrum of Ditto.*
E. *Spectrum of Light reflected from film of Mica.*
F. *Diffraction Spectra of slit, through a Nobert's grating*
G. *Ditto, observed through Prism*

every multiple of a given thickness of the transparent film, by supposing that the "particles" of light suffer alternate "fits" of transmission or reflection, at *regularly recurring* intervals or distances. Professor Tyndall supposes that he imagined a rotation during their progressive motion, and this is not improbable; but is only a supposition. If, then, light reaches the first surface of the film in a fit of transmission, it enters it and travels to the second surface; and if the thickness is such that it is in the same fit or phase when arriving at the second surface, it is again transmitted, and so is lost to view by reflected light. There is at that point, therefore, a dark ring; and obviously at every *multiple* of that thickness another dark ring. If, on the contrary, the particle is in the opposite or reflecting fit when it reaches the second surface, it is reflected and forms a bright ring.

It will be plain how, on either hypothesis, the "particles" or the "waves" of red light are *larger* than those of blue.

We can easily, however, test the two theories. Obviously all the light that has anything to do with the rings, according to the corpuscular theory, enters the first surface; and the "fit" in which it reaches the second has *alone* anything to do with them. On our wave hypothesis, it is the interference of waves reflected from *both* surfaces that causes them. We have not come to Polarisation yet; but it may be briefly stated that polarised light utterly refuses to be reflected from glass at a certain angle; and this polarised light we readily obtain by fitting a "Nicol prism" on to the nozzle of our optical objective.[1] All our light is then polarised; and when the long diameter is vertical and the Newton's lenses are adjusted at an angle of 55° to 56° with the beam from the lantern, none of it will be reflected from the top glass, or in other words, from *the first surface of the film.* And if two plain glasses were used, none would be reflected from the second surface either. But

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[1] For details and explanations on these points see Chaps. X. and XI. Only sufficient is stated here for the purposes of this experiment.

metal is subject to quite other laws, and does reflect light copiously under such circumstances; therefore, by substituting for the bottom glass one which has been silvered or platinised, we can still get reflection from the second surface of the film of air. On the corpuscular theory, we ought therefore still to get the rings. But we do not. There is *light* on the screen, but the *rings* have vanished, in the proper position of the Nicol; to be restored again when this is so turned round as to restore reflection from the first surface also.

Further yet; if we next adjust the lenses so as to meet the light at a still greater angle (from the normal) than that of polarisation, and thus *partially* restore reflection from the first surface, on rotating the Nicol we get a complicated and beautiful phenomenon, first discovered by Arago; viz., in one position the rings are of certain colours, and when the Nicol is rotated 90° they show *complementary* colours. Detailed explanation of this is here impossible; but it can be understood how we thus prove absolutely that the rings are due to the mutual actions of the rays of light reflected from *both* surfaces of the film. We may prove this in yet another way, by substituting for the glass and metal surface, two glasses of widely different refractive powers, whose polarising angles are therefore also different (§ 130). We can then adjust the beam of light to either, and in either case, by destroying reflection from *either* surface of the film, we destroy the rings. This last method of demonstration is, however, only suitable for private experiment.

106. **Spectrum Analysis of the Rings.**—We further investigate the matter by bringing to bear our never-failing method of spectrum analysis. Cover the pair of Newton's lenses with a disc of black paper or card, having in it a slit, say, $\frac{3}{16}$ of an inch wide, and reaching all across, exactly over the centre; the slit then crosses all the bands at right angles, and the appearance, or image on the screen when focused there, is like one of the bands in Fig. 107. The whole arrangements

are shown in plan in Fig. 108. The lantern must be turned considerably away from the screen, so that the reflected beam may have a small angle of incidence; or else, as the glasses are so thick, the light from the film will not be able to emerge from the narrow slit by which it enters, and there will be only an image of a white slit as reflected from the *upper* surface of the top glass, and none of the portions of rings, which is what we want. The reflected slit is focused by the loose lens, F, at about the screen distance, but must be considerably divergent from the screen to allow for refraction by the prism, P, which gives the spectrum on the screen, S. The lenses are drawn much larger in proportion for the sake of clearness.

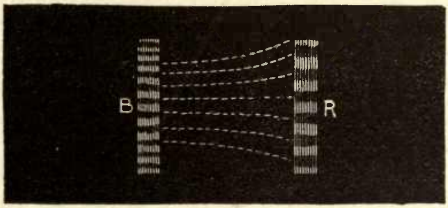

FIG. 107.

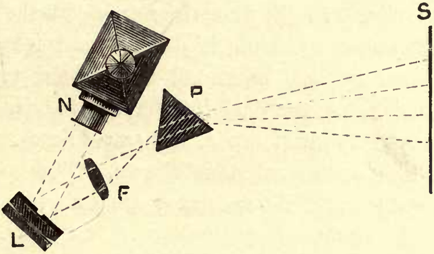

FIG. 108.—Spectrum Analysis of the Rings.

Thus passing the image of the slice of rings from white light through the prism, and throwing its spectrum on the screen, it is easy to see what we may expect if the wave theory be correct. Dr. Young saw it long ago, and in his "Lectures" he has *drawn* what he foresaw clearly with the eyes of his mind, though there is no record that he observed it in actual fact as we are about to do. Seeing that red light gives us bands of a certain width, as at R in Fig. 107, while blue light gives us narrower bands as at B, by drawing the imaginary lines as dotted, we can see what must occur when all the colours are dispersed into their several places in the spectrum. We *must* get, unless all our theory is wrong, the beautiful appearances shown in B, Plate III.; the spectrum of the slit being crossed by parabolic dark lines, which will show exactly the waves *cut out* by interference at every thickness of the film. Such a spectrum, with its parabolic interference bands, stands before us on our screen.[1]

The flat soap-film may be analysed in precisely the same way. Arrange for a parallel beam, and place the cardboard or adjustable brass slit on the nozzle, as for previous spectrum-work. The slice of light from the nozzle will then sufficiently mark the slit whose spectrum is desired, and may impinge at any convenient angle. When all is adjusted, take up a fresh film; and as it thins, the dark interference bands, showing the waves destroyed by interference, will *travel* across the spectrum steadily, as long as any colour is shown. The appearances of the flat soap-film and its spectrum are shown at C, D, Plate III.

The student can observe these phenomena directly through any form of prism; and nearly all the phenomena described in this chapter can also be seen privately, without any lantern or other expensive apparatus whatever.

107. **Phenomena of Thicker Films.**—Towards the edges of a pair of Newton's lenses the rings of colour seen in white light disappear; and some students realise with difficulty why

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[1] To the best of my belief this beautiful experiment was first publicly made with the lantern by Dr. Tyndall.

this is so, when the films reach a certain thickness. There are two reasons. One is very much the same as the reason why we could not get a pure spectrum from a wide slit. (§ 55.) Interferences are produced, up to a certain point; but so many very narrow rings or fringes are mingled, so close upon one another, that the visual effect is white. Homogeneous light will show rings in much thicker films, and is one proof that this is so. Spectrum analysis of a film not so thin is another. With care, a film of mica can be split so thin that, while it appears to reflect perfect white light, if a slit of this light be analysed, by blacking the mica all but a narrow stripe, and then treating this stripe of reflected light like the slice of light from Newton's lenses, the spectrum will be seen *crossed* by numerous straight interference bands. Such a spectrum from a film of mica is shown at E, Plate III. But there is another reason. When the film reaches a still greater thickness, it will also be seen on consideration that the two reflected rays into which each original ray is divided, are so far *separated* by refraction, that they are no longer close enough to interfere with each other at all.

Thin mica films may be employed in yet another way. Project a spectrum from a slit as usual, and across the path of the rays hold the film obliquely. A portion of the rays are then transmitted direct, while a portion are reflected within the film and then transmitted, after losing a certain distance as before. Again the spectrum will be crossed by beautiful interference bands, though hardly so distinct as by the preceding method.

It is very clear that the thicknesses at which the light and dark rings occur, must give us definite information as to the *wave-lengths* of the different colours of light. This point will, however, be better explained a little farther on (§ 117).

108. **Thin Films and Sound Vibrations.**—The most elegant application of the colours of thin films in physics is due to the researches of Mr. Sedley Taylor, and relates to the

vibration of a telephone plate. It is well known that, by the variable attraction of a magnet under the influence of variable currents, and vibrations thus caused in a thin sheet of iron, the most complex sounds of the human voice, or other instruments, are reproduced by another sheet of iron at the other end of a telegraph wire; but it is very difficult to realise how complicated speech can be reproduced by such simple means. By stretching a soap-film over an aperture in a plate laid over a resonator, and exciting the vibrations of the air contained in the latter, Mr. Taylor obtained most beautiful figures which elucidate the matter, by showing how complicated these vibrations are. Later on Mr. Tisley constructed the *phoneidoscope*, which, when sung into through an open mouthpiece on the end of a tube, shows the same phenomena in a film laid horizontally over the other end of the tube. The scale of this instrument is, however, too small for lantern work, and it is very difficult to avoid constant bursting of the film. After many trials an apparatus was constructed, which easily gives magnificent phenomena, and the essentials of which are shown in Fig. 109. A is any vessel open at both ends, 2 to 3 inches across at the top, and with a neck at the bottom large enough for an inch vulcanised india-rubber tube to stretch a little

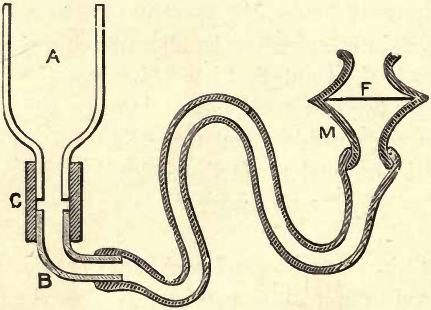


FIG. 109.—Principle of Lantern Phoneidoscope.

tightly over an elbow, B, connected with it by a piece of rubber tube, C. A piece of a common bottle, cut round the body and neck, and ground flat at each end, would suffice, or a tin funnel with an elbow at the bottom and a flat ring soldered flush round the top will answer admirably. The whole can be fitted into any thin box, the funnel projecting through a hole cut in the top. The other end of the elastic tube is stretched over the neck of a kind of telephone mouthpiece, M, furnished with a membrane, F. A soap-film being laid over A, and used as presently described, can readily be focused on the ceiling or an overhead screen in the same way as the ripples in Fig 31.

But I now use a more complete and convenient apparatus constructed for me by Mr. C. Darker, which works direct to the ordinary screen, and is shown in Fig. 110. The diagram explains itself, the dotted line showing the course of a slightly converged beam from the condensers, and how the first mirror brings down the light upon the mouth of the funnel, and the second redirects the rays reflected up from the film into a horizontal path; the focusing lens (of rather long focus) focusing the image. The mirrors have some adjustment in two horizontal slots in the back-board. The funnel should have apertures or notches at the top to allow air to escape from under the film, and be so mounted that it can be withdrawn from the kind of open box in which it fits, when its place can be occupied by a vessel of water or mercury, or other apparatus. A black card will need to be adjusted against the side of the apparatus next the screen, high enough to prevent any stray direct light from the lantern, or other than the reflected rays, passing the apparatus. My first mouthpiece was made of wood,

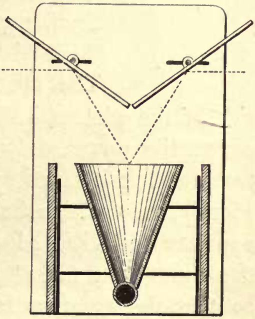


FIG. 110.

as in Fig. 109, with a vibrating diaphragm of thin mica at F; but this sometimes rattled, and I prefer it as in Fig. 111, with a membrane of very thin india-rubber. A membrane of any kind, if thin enough, does not interfere with true sound vibrations, but prevents the film being prematurely ruptured by any direct blast of air, which might occur with an open mouthpiece. The india-rubber speaking-tube may be any convenient length, and it is more impressive if connected with a sufficient length of metal pipe to reach to the other end of the room.

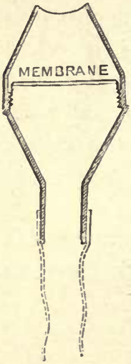


FIG. 111.

All being arranged, some plates must be prepared, of metal or very thick card, $3\frac{1}{2}$ inches or 4 inches diameter, with openings in the centre of different shapes; the best effects are from circular, square, and hexagonal apertures, which should be about $1\frac{3}{4}$ inches or 2 inches diameter. The apertures should be *bevelled* towards one side of the plate (this is done because the film will, by its contractile power, draw flat to the smallest side of the aperture), and if of card, well varnished to resist the moisture. Finally, they are blackened, and we are ready for work. The apparatus is adjusted so that one of the plates laid across the top of the funnel lies nearly level, and all is arranged so that the aperture is truly focused on the screen. Then we dip the end of a strip of card, rather wider than the apertures, in a saucer of soap solution, and drawing it carefully over the *smallest* side of an aperture, readily cover it with a film. (Use no more solution than necessary.) Several plates may be covered at once to avoid delays. Hold the plate at an incline, or upright, till interference colours begin to show; then lay it centrally on the funnel, with the soap *downwards*, so that a dead black dry margin surrounds the film. If all is right, we have an image of the film on the screen. Be sure all is focused properly, and that all light possible is condensed upon the film.

Then take the mouthpiece, or let some one else do so at the other end of the room, and sing into it. Not only every note, but every different vocal sound on the same note will be represented in different, complicated, and most beautiful kaleidoscopic patterns, very poor ideas of a few of which are shown in Fig. 112. At first we may get only shadowed figures, but with a little practice we soon get exquisite colour figures, with symmetrically-arranged whirling vortices; and if we sing a song, every change of note will be optically represented on the screen by a corresponding figure. Employing a mouthpiece with a vibrating plate or membrane, there is little risk (as with Tisley's form of apparatus) of bursting the film, and a good tough one will sometimes last a quarter of an hour. If the film breaks too soon, it shows either that the solution is not good, or that the plates have ragged edges, or are too dry: metal ones, which are best, hold the film more smoothly if heated and smeared with a thin coat of melted paraffin.

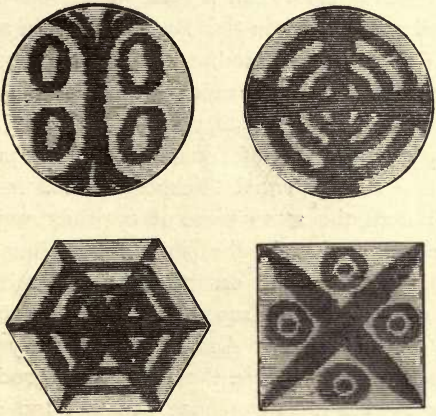
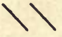


FIG. 112.—Phoneidoscope Effects.

This is one of the most magnificent optical experiments, and very easily shown. With the apparatus in Fig. 110 interesting modifications can be made, by withdrawing the funnel and tube, and laying larger plates with apertures and films upon the box itself. If then a tuning-fork on a resonance-box be excited, and the open end of the resonator be presented to the open side of the box under the film, strong stable vortex figures will be caused; or a cornet blown whilst presented in the same way will also excite most powerful vibrations.

109. **Colours of Thick Plates.**—Thick plates of glass, ground and polished with sufficient accuracy, can be made to exhibit interference colours in several ways; but only one or two can be demonstrated in the lantern. Jamin showed that if a pencil of light was reflected at an angle of about 45° from a plate of thick glass, and the reflected pencil again received at the same angle on another plate, so as to be finally reflected in a direction parallel to that of the original pencil, provided the plates were of *exactly* equal thickness (which is secured by cutting both from the same piece of optically worked glass) interference was produced; the pencil reflected from the first surface of the first plate and second of the second, interfering with that reflected from the second surface of the first and the first surface of the second. Accordingly, the very least deviation from parallelism between the two plates produces interference fringes, until the divergence becomes too great. For projection the apparatus is arranged in the form known as *Delezenne's analyser.* In this instrument the two plates are arranged so close to each other in comparison with their area,  that the original pencil of light (here supposed to come from the top of the page) cannot pass the edges of both plates. Each plate is mounted on the inner flat surface of a circular cell resembling in shape the half of a collar-box, one being capable of rotation inside the other in the same way as that well-known article: in this case the flat lid and bottom of the box would be parallel to the lines of this page, and the axis of revolution parallel to the side of the page. Then by slightly rotating the

cell bearing one of the plates, beautiful interference fringes are produced, exactly resembling Savart's bands (§ 201 and Fig. E, plate 7). The parts of the brass mount representing the lid and bottom of the collar-box are pierced with apertures, so adjusted as to prevent any light from passing the apparatus, except that which has been reflected from the two glass plates. These last may be either silvered on the back, or not. The individual student has only to look through Delezenne's analyser at a window, or sheet of white paper, or any fairly bright surface, to see the fringes.

Newton's experiment with a thick glass concave mirror is also of great beauty and easily projected. The mirror should be of about three or four feet radius of curvature. The face is carefully cleaned, and then somewhat dulled all over by a film of weak milk and water laid on with a clean sponge: milk alone is far too opaque, and dusting with lycopodium powder, which I have seen done in alleged substitution, gives rise to rather different *diffraction* phenomena, as described in § 114. The radiant must now be adjusted in the centre of curvature of the mirror, so that the reflected rays focus again at the same point. With a good jet or the arc light, a very good plan is to send all the converged light possible, from the lantern through a small aperture on the nozzle, the aperture thus becoming the focal radiant; and around the nozzle to adjust a screen of white card with an aperture in the centre for the nozzle to protrude, precisely as in the rainbow experiment figured on p. 75, except that here the parallel pencil is replaced by a diverging one, collected and thrown back by the concave mirror. Brilliant circular iris-coloured rings will now appear on the white card screen, surrounding the aperture as a centre. If the mirror be slightly deflected so as to separate the focal image from the radiant centre, the rings will surround a centre midway between the two, and the appearances of this centre will vary remarkably with changes in its position.

In this experiment, the interference is produced between pairs of rays or very small pencils irregularly scattered by the dulled surface of the mirror: the one ray, that scattered on entering the glass; the other, that scattered on leaving it after reflection from the silvered back.

Or the arrangements may be varied by using the naked jet and lime-cylinder quite out of the lantern, and adjusting it with the incandescent face towards the mirror. The lime itself will shield the light from the large projection screen behind; or if the incandescence be too great for this, a small opaque screen should be arranged to do so, and a cylindrical case round the mirror stop stray light from the room. Then the rings will be projected in air in the focal plane of the lime-cylinder, and a large lens of long focus will produce a fair image of them upon the screen.

A glass mirror for this experiment must be optically worked: the common cheap ones do not suffice. A student may, however, perform it with a good piece of thick plane looking-glass alone. Dull the surface as before, and support the looking-glass piece at one side of the apartment. Taking a candle or other small flame in the hand, go to the other side, and hold the flame so that the image is seen in the centre of the dulled mirror when the eye is as near it as possible. Broad fringes will be seen in the mirror.

110. **Fresnel's Mirrors.**—There are many other ways of producing interference between two rays of light than the use of plates or films; but not all of them are capable of employment with the lantern, owing to the small amount of light which can be used not being sufficient to be visible when spread over a screen. Fresnel, for instance, letting a cone of light from a luminous point fall upon two mirrors very slightly inclined together from the same plane, formed interference fringes. The arrangement is shown in Fig. 113, where a pencil of rays from the sun is converged by the lens to the one point or line of emission we have already found necessary. A test-tube filled with water as a cylindrical lens answers perfectly

well, or the line of light *reflected* in sunlight from such a tube filled with mercury will also answer. The diverging rays beyond the focus are then received upon the two mirrors, M m, m N, and if the inner edges or junction line of these be very slightly depressed, it is manifest the reflected rays will somewhat cross each other, and that light from both will appear on a portion of a piece of card held as a screen at S. On this portion will be found dark and light, or coloured stripes, due to the interference of the waves. Two pieces of the *same* glass blacked on the back and laid on a piece of cloth on a flat board, the inner edge of one being depressed a little by the end of any pointed tool, will enable the student to perform this instructive experiment. If the light from the lantern be made to diverge from an extremely narrow slit, and the mirrors be arranged at several feet distance from it, the dark fringes may be observed by the few who can gather round the apparatus; but on the screen the fringes are too faint to be seen.

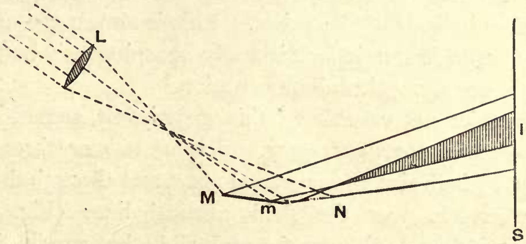


FIG. 113.—Fresnel's Mirrors.

111. **Fresnel's Prism.**—Fresnel also caused two beams to interfere, by interposing in the diverging cone a double prism of very small obliquity, called an "interference prism," with the same result. Here, too, the light is very faint for a large screen, but some approximation to the effect is possible with a powerful jet, and still more with the arc light. The prism must be good, and ground with a very *small* angle; when the bands are broadest. The lenses should be removed from the

optical front, a slit placed on the nozzle, and a lens mounted in a wooden frame placed in the optical stage, so as to focus all possible light upon a short slit, the rays diverging from this. In the diverging rays the bi-prism is placed, not far off the slit, and carefully adjusted for parallelism with the slit. If the prism is a good one, and the jet powerful, most eyes will discern perpendicular fringes on the screen in the brighter band where both sides of the prism unite their rays. Often they show more plainly by using a piece of very transparent red glass; and they are generally improved by using an achromatic lens of several inches diameter and 6 or 8 inches focal length, to focus upon the screen, not the prism or any other actual object, but the fringes as they appear in the focal plane of the lens, a few inches in front of the prism. This is almost the only case in which an achromatic lens is really conspicuously better than a simple one for optical demonstration.[1]

With a jet not capable of this experiment, something may yet be done in a rougher way. Prepare two or three sliders, the 4 × 2¼ inch size, of blackened glass, and through the black, cut or scratch, over the field, vertical lines (Fig. 114) of uniform width and distance for each slide, but varying in these characters on different glasses, the medium width being about one-thirtieth of an inch. (Only one is really necessary, but it will be found that each screen distance shows the best phenomena with its own gauge of bright lines, which must be found

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[1] I have obtained the best screen effects with the projection microscope. On the compound or table microscope the experiment is a very easy and beautiful one, a very small bi-prism sufficing. This is laid on the stage, fixed or mounted on the middle of a glass slip. An inch or more below, in the sub-stage, is adjusted a disc or piece of glass blackened all over, with one bold line scratched in the centre, on which is condensed as much light from the mirror as possible. The bi-prism has only to be got in line and in centre for the fringes to appear. They may either be looked at with the eye-piece alone, or a low-power objective may also be used, not to focus the prism, but a plane above it. Either the eye-piece or the objective focuses for vision the state of the fringes in its own focal plane.

by trial.) Place in the optical stage and focus: then against the nozzle, N, hold, or fit in a tube which slides on it, the double prism, P, as in Fig. 115, which will give two images, whereof

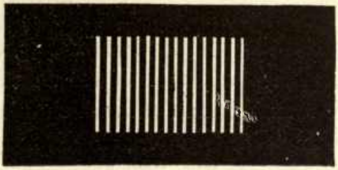

FIG. 114.

one set of slits will, more or less, overlap the other. If the slits are the right gauge for the lenses and screen distance, we get colour; and it can readily be shown, by covering one half

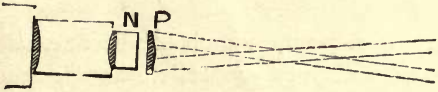

FIG. 115.—Fresnel's Prism.

the prism, that nearly all this colour is due to the interference of the two sets of waves.[1]

112. **Irregular Refraction.**—Another means of causing interference is by irregular refraction, causing *retardation* of portions of the light. Such are the phenomena of what Dr. Young called "mixed" plates. Provide a few discs of plate glass about 2 inches diameter. Carefully clean two discs so that they show colour when pressed together, and then intro-

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[1] The private student will have no difficulty at all with this experiment. He has only to cut in a black card a set of slits, about one-sixteenth of an inch in width and distance, and hold this at arm's length against a bright sky or the opal globe of a lamp, with the slits perpendicular. On now holding the double prism close to the eye, with the centre line over the pupil, he will at once see conspicuous colours. Such prisms an inch square cost from 2*s*. 6*d*. to 5*s*. each.

duce between them a bit of butter or suet the size of a large pin's head, and some clean saliva or a drop of water; or the froth of white of egg well beaten up will do; or fine soap-lather. Work together with a circular movement, and gradually a film of mixed grease and water, or albumen and air, &c., will spread between the plates. Now it is plain that the light which passes through a molecule of the denser portion of this mixture is more retarded than that which passes through the other; and hence we find, on looking through the film at a luminous point, there are beautiful halos of colour. Or if we place in the optical stage a black card in which a few small holes are made, on focusing the holes, covering the nozzle with another black card pierced with a $\frac{1}{8}$-inch hole, and holding a little in front of this (the exact distance must be found by trial) the "mixed plate," the images are surrounded by coloured halos, the colour of course depending upon the thickness of the film.

To the same cause must probably be referred the curious phenomena seen when an equal mixture of glycerine and spirits of turpentine is shaken together. What is known as diffraction will not account for it, since there is no approach to a spectrum; but it is completely accounted for by the unequal retardation of the light by the two media in small molecules, which only mix mechanically. On looking through the mixture at any illuminated objects, they will be seen fringed with colour, the colour changing as the liquids again settle, till only a coloured line is seen in the fluid itself where the two are in contact. I have only tried the experiment thus, but by making a small closed tank with parallel sides, there is not the slightest doubt some beautiful phenomena might be projected on the screen.

113. **Diffraction.**—One of Newton's two great difficulties about the Undulatory Theory was, that if it were true, the ether-waves ought to bend round the edges of bodies into the shadow. It appears strange now, that even the few experiments he made in diffraction did not suggest to him that this is precisely what

does happen. If we hold any opaque body, such as a black card, in the rays from a very small point or line of brilliant light, such as already described, we find there is no sharp shadow, but a series of coloured fringes due to interference, both within and without what should appear as the geometrical shadow. Dr. Young, who first pointed out the true character of these fringes, supposed them due to the interference of the direct rays with those reflected at a great obliquity from the edges of the body. This has been shown to be incorrect; and all the fringes have been proved to occur from the interferences of the *secondary waves* shown in Fig. 80, when separated from the "grand wave" by the opaque body. They can be observed without any apparatus at all, by receiving on a card a shadow from the planet Venus at its brightest, in an otherwise dark room.

But more beautiful phenomena are within our reach, the nature of one class of which is best seen from a simple experiment without the lantern, which should be made by every student. Cut a slit $\frac{1}{8}$-inch wide in a black card, and hold it in front of a flame so as to be brightly illuminated. Blacken a bit of glass, and scratch with a needle a straight line on that. Hold the scratch close to the eye, and look through it at the slit, held at arm's length, both being vertical. We see the slit in the centre, and on each side of it are a *series of spectra*, and we thus prove conclusively that the waves of light *do* spread out laterally from the second slit, becoming visible under these circumstances partly because all stronger light is cut off, but chiefly because we stop off the greater part of the main wave. (See Fig. 80.) The spectra, of course, represent overlapping images of different colours, as we can see if we cover our first slit half with blue glass and half with red; we then get a series of red images *farther apart* than the blue images, precisely as in previous experiments. The reason why we get the dark spaces between, and not one unbroken band of light, is that at certain intervals, which can be, and have been, exactly calculated, the waves from, say, one edge of the slit, interfere with the waves starting from the other edge, or some other point in it. From one edge the path to the eye is *longer*, and we have already learnt that retardation means extinction of certain colour-waves. (See § 117.)

114. **Gratings.**—The foregoing experiment theoretically ought to be shown by the lantern, and it has been stated that it can be; but I have never been able to do so, for the reason already given; the light passing through the second slit is not sufficient. Undoubtedly the spectra must be on the screen; but they are too faint to be perceived. We must get "more light," and we are helped in this by the fact, that if we arrange a number of slits *exactly* at equal distances, their various interferences and correspondences all fall at regular intervals, depending partly on the width of the slits, and partly on their distances apart. Such is what is termed a "grating," or series of very fine light and dark lines. If fine enough, such an assemblage of slits practically cuts out, at each point on the screen, all but one single wave-length, and so produces *pure* spectral colours only; whereas the other interference colours we have seen are mixtures of residual colours.

Nobert has ruled gratings with 3,000 and 6,000 lines to the inch, and photographic copies of the first of these are sold at a guinea, or less, and produce most beautiful phenomena. Placing a slit, say $\frac{1}{8}$ inch wide, in the optical stage, and focusing, we hold the grating in front of the nozzle, with its lines parallel to the slit. There are at once projected on the screen, on each side of the central image, a most beautiful series of diffraction spectra (see F, Plate III.). Two similar gratings *crossed* give beautiful spectra of a small hole about $\frac{1}{8}$ inch diameter, especially if the aperture be illuminated by the pencil attachment shown in Fig. 2, but without the front concave lens; or the light may be condensed on the aperture by a lens in the optical stage as previously described. There are not only perpendicular and horizontal spectra, but also diagonal ones. The finest effects are, however, produced by placing in the optical stage a symmetrical pattern of *several* small holes in a thin metal plate—say eight arranged in a square; but the pattern, size, and distance must be found by experiment and adapted to the gratings used and the screen distance. If properly adjusted, and with sufficiently brilliant light, on rotating one grating, most beautiful diffracted patterns will appear on the screen.[1] A circular grating, two or three inches in diameter, scratched on glass, gives brilliant circular rainbows, when interposed in the path of the rays from a small aperture focused on the screen. Any kind of grating gives most brilliant effects if held close to the eye, and looked through towards any small naked flame at some distance, or still better towards an arc light.

Another attractive method of observing diffraction phenomena is to cover the object-glass of any telescope—one such as can be bought for 7*s.* 6*d.* will do—with caps of black card, in each of which is pricked or cut one or more very small holes of various sizes, arranged in different patterns. Or the cap may be of blackened glass, on which is scratched very small any regular curve or figure, such as a tiny circle or square. On looking through the telescope thus furnished at a bright star, beautiful diffraction figures will be seen : or if the telescope be directed to a small hole in a plate close in front of a good limelight, the phenomena will be gorgeous beyond description. This is known as Brooks's apparatus.

But such apparatus is not needed to show diffraction. Two simple slits have already been mentioned. Even the fingers will

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[1] Mr. C. J. Fox, F.R.M.S., first showed me this beautiful experiment in the microscope, to which he had adapted it, and in which the effects, owing to better illumination, are far superior. For that instrument the apertures, pricked in a blackened circle of paper, are focused by a low-power objective, and the gratings mounted over the eyepiece. With the lantern, the parallel beam from even the limelight needs to be condensed by an extra lens into the smallest area which will cover the apertures.

show fringes if *nearly* closed and looked through at a distant candle. With care, any one may rule on smoked glass for himself, with a sharp needle, a grating of 120 lines to an inch, and even this will give very perceptible spectra. Wire-gauze is obtainable 120 meshes to the inch, and sometimes 150 meshes; and this will give perceptible phenomena, especially if gauze and lens be both five or six inches in diameter, greater number of lines increasing the brilliance and "resolution." So also will a selected bit of the very finest cambric; but a good piece can only be found by experiment, when it should be mounted between two glass plates. Even more simple objects are at hand. Get a broad pheasant's body feather (some birds' are better still, but this is easily got; most fowl feathers are too coarse), and mount it between two glass plates, blacking out all the space the feather does not cover. Focus on the screen a small hole in a black card, and interpose the feather; or look through it at any naked gas-light; again we get attractive diffraction phenomena. A very familiar example is found on looking through almost any railway carriage window at night, at one of the lamps. The dripping of the rain and dust, and the process which goes by the name of cleaning, combine to form tolerably perpendicular lines on the glass, and these draw out the luminous point into a long band. Usually this is only vaguely luminous,—the lines being irregular, various colours overlap and produce white—but on one or two occasions in the course of several years I have seen colours.

Halos are produced in a very similar way. If a small distant flame be looked at through a glass dulled by the breath, colour will be seen: and if a piece of glass be dusted with lycopodium powder, very good halos will be seen through it. Satisfactory effects from such dusted glasses on the screen, will however depend upon the *size* of the dusted glass, greater size increasing the resolving power as with the gauze. If the dusted glass be six inches in diameter, and it be held close to a lens as large, so as to employ the whole surface, beautiful halos will be seen, even with lycopodium; but there are still better spores of black or purple colour to be sometimes obtained, such as those of *Elaphomyces granulatus.*

Most beautiful lantern projections may also be produced from perforated cards, such as can be bought for book-markers at a penny each. Several sizes are made, the smallest being about twenty-five holes to the inch; purchase one or two of each size, and blacken all but the smallest, which would fill up or choke.[1] Cut circular discs to fit such standard wooden frames as already mentioned; and fix in frames, by a spring circular wire, two specimens of each size. First place in the optical stage one such slide (generally a medium gauge does best for this; but again, much depends on the screen distance). On focusing, we of course get images of the circular holes. Now gently *run in* the focusing-tube a little farther, so that the focus is projected rather *beyond* the screen. The pencil of light from each aperture now interferes with its neighbours, and we get a more or less decidedly *coloured* pattern, which varies as the lens is moved in or out of the focusing-tube; at two or three feet away from the nozzle, the colours are pretty vivid. Much interest will be found in the various interference patterns given even by single cards in this way. But now add a *second* slide in front of the other. If the frames are $\frac{3}{8}$ of an inch thick, and the slides are inserted "the same way," the cards will be that distance apart, which, with a screen five feet off, is for most lenses a good distance; if a little more or less interval is necessary, one slide may be reversed. The pencils of light from the posterior holes are now further diffracted by the second set. As a rule, I have found the best effects at four or five feet distance, the *back* card being focused somewhat short of the screen, and from medium gauge cards; but fine effects are produced at that distance (which should not be

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[1] An alum-trough is desirable, or the black card may burn with the heat. Perforated zinc is not troublesome in this way, but cannot be got in the smaller gauges.

exceeded with a lamp or burner) with most of the cards, or by a coarser one behind with a finer pattern in front. A little experiment will soon be repaid by most beautiful coloured tartan patterns, especially if the front card can be rotated in a frame such as is described later on for polariscope experiments ; all produced by the interferences and diffractions of the small pencils of light. With the limelight and a screen distance of ten or twelve feet, I have found the best effects from using both cards of the finest pattern, placed back to back, so as to be only $\frac{1}{8}$ inch apart. As one card is rotated, beautiful effects will be produced when the right focus is got; and in certain positions it will be found that a little alteration in *focus* only, appears to *rotate* large squares of the pattern in a most beautiful manner. But the arrangements are different with each objective and screen distance. The small white screen will be found very handy to show the varying effects at the shorter distances ; and any experiments intended for exhibition should be carefully worked out at *exactly* the distances that are to be employed, or the effect may be found quite different from that intended. Any experimenter, however, may depend upon finding great pleasure in this direction. The private student may hold one card close to the eye, and the other at a little distance.

115. **Striated Surfaces.**—Lastly, light *reflected* from very narrow lines or grooves also gives us interference. Turn off the lantern parallel with the screen, and placing a perpendicular slit in the optical stage, focus it as reflected from a bit of plane glass held close to the nozzle at an angle of 45°. Then substitute for the plane glass a grating held in the same position ; the image of the slit is now flanked on each side by spectra, just as when transmitted light was used, only not quite so bright. If no grating be possessed, get a finely-coloured piece of flat polished mother-of-pearl, or one of those beautifully-coloured haliotis shells found in Jersey, which can be bought for one shilling almost anywhere, or a finely-coloured

pearl card-case will do; the main thing is to select a richly-coloured specimen. There is really no colour *in* these shells whatever: it is entirely due to the interferences of rays reflected from the countless little grooves which cover their surface, as can be proved by taking a good impression of one of the best bits in black sealing-wax, when the indented wax will show the colours of the pearl. Adjust the shell or piece of pearl like the soap-film, condensing all the light on it at 45°, and focusing with the loose lens. The coloured image shows a kind of glowing "transparency" on the screen, very beautiful; but as we now gently turn the shell so as to change the angles, *the colours change*, showing that they are not fixed, but due to interference.

Even a peacock's feather gives beautiful phenomena treated in the same way, but some of the colour appears to be more of the nature of that from a thin surface film. If we mount the end of one by two black ligatures sewn through a black card, and treat it like the pearl, we shall find that at different angles we get very different colours, passing from deep purple to brilliant green. This is a beautiful experiment, but requires the lime-light, at not too great a screen distance. For all these latter experiments, the handiest plan is to prepare a small blackened tablet like Fig. 116; a thin piece of blackened deal, D, being glued on a boss, B, into which is driven a tube, T, fitting in the sockets of our pillar-stands. The feather, or shell, or other article, can either be fastened direct to the tablet with two elastic bands, if solid and small enough, or the feather on the black card can be affixed by two blackened drawing-pins. The object can then be either rotated on a

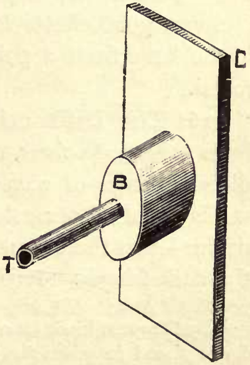

Fig. 116.—Tablet for Objects.

horizontal axis, or the angle of incidence and reflection rotated vertically by turning the pillar.

The metal buttons engraved with very fine lines, formerly made by Sir John Barton, then Master of the Mint, and still known as "Barton's buttons," are amongst the most splendid examples of the interference of reflected light. They are very scarce now, none having been made for forty years; but a few are treasured here and there, and when the polish is well preserved, they glow with brilliant colours impossible to describe.[1] Any who possess one, in good condition, may produce an exquisite screen projection with the lime-light by taking out all the front lenses, placing a $\frac{1}{4}$-inch aperture in black card in the ordinary lantern-stage, and allowing the beam from this to be reflected from the button and focused on the screen. Or the naked lime-light, through a small aperture in a cap slipped over the empty condenser-cell, may be *focused* on the screen, which gives more light; as will the pencil attachment, Fig. 2. Various small spectra will be seen arranged in a beautiful stellar pattern, depending on that of the button. I have seen also very good effects from the finest cut that can be produced in the lathe from a pointed tool on the flat surface of bright metal.

116. **The Diffraction Spectrum.**—In all these ways we have produced colour, or dark fringes, by the interference of different series of waves. It will be manifest that, as before, we have got all our colours solely by suppressing or quenching colour—that the colours are precisely of the same character as the dark fringes. It is equally manifest that since, as a rule,

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[1] By the great kindness of Mr. John Barton, grandson of the inventor, I was placed in possession of a fine set of these buttons or "Iris ornaments." I learnt from him that the dividing engine, constructed for Sir John Barton by Messrs. Maudsley and Co., had been always in possession of the family since; but that since his father's death, no one for a long while could use it efficiently. After many trials, however, Mr. Robert Barton, in Australia, succeeded in producing good results, and some specimens of his workmanship were shown at the Melbourne Exhibition of 1880–81.

only one particular wave-length can be *completely* extinguished at any given point, the colours we see are not pure, but compound residuals, or made up of the residue of the spectrum. The only exception is in the case of gratings, which, by the orderly sequence of successive extinctions, cut out all the colours except one wave-length at a given point. A little thought will lead to the conclusion that in these grating spectra we must therefore get the colours, or Fraunhofer lines which locate them, in the *real order and proportion of their wave-lengths*, and not as affected by the various or anomalous dispersions of refracting prisms. This is so; and the fact makes grating spectra, though less brilliant than those given by a prism, owing to the large suppressions of light which produce them, especially valuable to the physicist.

This difference in the spectra, and the uniformity of diffraction spectra as compared with those produced by a prism, can easily be shown by experiment. Diffracting the pencil from a brilliant small aperture by a parallel grating, and further diffracting the *spectra* thus produced by a second similar grating, held with its lines at right angles to those of the former, we have already seen (§ 114) that we get a most beautiful series of diagonal spectra. This, of course, must follow from considerations already discussed, and the greater distances apart of the red images than the blue. All these diagonal spectra are perfectly *straight*. But if, instead of a second grating, we use a prism, with its refracting edge at right angles to the slit, it is not so. We still disperse the central pencil of white light, and refract each spectrum produced by the grating; and, as before, the blue portions of the spectra are more deflected than the red. But the deflection is no longer *proportional*, but dependent on the special dispersion of the prism; and hence the refracted spectra now appear as parabolic curves, represented at G, Plate III.

117. **Measurement of Waves.**—We have, in the phenomena of interference, various means of measuring the *lengths of*

the waves which produce any given colour. For many and obvious reasons such measurements are easiest taken with monochromatic light; and the simplest case is that of the light from a slit or point passing through a second slit (§ 113). Let A B be a highly magnified representation of the second card and C D of the slit in it. The rays which pass perpendicularly through C D will none of them be retarded; and therefore produce on the retina or a screen an ordinary white image—the central white band. But as the card A B stops off the main wave-front (§ 67), every particle of ether in motion all across the width of the slit produces new secondary waves spreading right and left of the perpendicular direction: let us take any given inclination, C E, D F. Then drawing C *w* perpendicular to the course of the ray, we see that the waves from D have farther to go than those from C by the distance D *w*. Assume that at this inclination D *w* is a wave-length of the colour employed, and number the supposed ether particles across the slit from unity onwards,—then we see that from 4, the central particle, the waves are half a wave before those from D, and half a wave behind those from C. But still further, the rays from 1 will be half a wave before, or in complete discordance with, those from 5, 2 with 6, and so on: every single ray finds another in complete discordance with it somewhere in the slit: obviously therefore at *this particular angle there must be a dark band.* Farther to the right or left the relations will alter, and there will be a bright band, to be succeeded by other dark and bright bands. A general proof of the correctness of this reasoning is found in the fact, that plainly, according to the

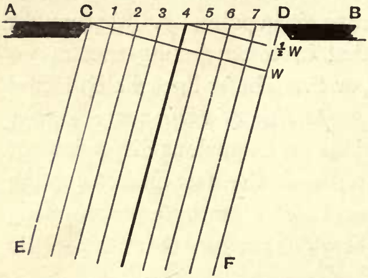

Fig. 117.—Nature of Diffraction.

theory, the narrower the slit the greater must be the angular distance of any given band from the central image. This must be, because it will demand a greater obliquity to make the necessary difference of paths from the edges of a narrower slit. Experiment shows that this is the case.

Upon this hypothesis we can measure exactly the length of a wave, as in the diagram, Fig. 118. Draw the line A B to represent the card as before, with C D, the slit in it, and C E, D F, the inclination for the first dark band from the centre of the field. With the radius C D describe a semicircle, and from C also draw C w as before, perpendicular to D F; then D w is one wave-length, and x y is the angular value of the obliquity of the dark band. Inspection shows us that the angle x D y is necessarily equal to D C w; and as D w is for such a small distance practically coincident with a segment of the semicircle, we only have to take the proportion of 180° (the semicircle) to the angle D C w (the obliquity), and the same proportion must exist between the linear *length* of the semicircle and that of the wave. Schwerd found that with a slit of 1·35 mm. the angle D C w was 1′ 38″, the ratio of 180° to which is 648,000 to 98. The linear length of the semicircle is 4·248 mm. It follows that the length of the wave, of the colour employed in his experiment, is about the $\frac{1}{40000}$ of an inch.[1]

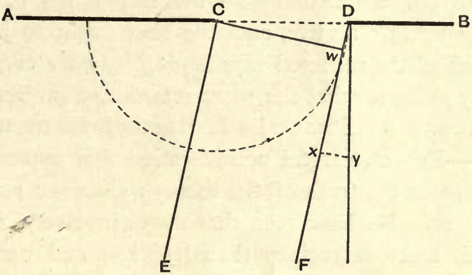

FIG. 118.—Measurement of Wave-length.

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[1] The phenomena of gratings are too complex to enter into here; they are admirably elucidated in Müller-Pouillet's *Lehrbuch der Physik*.

We may reason in the same way from thin films. The thickness of the film at the first *bright* ring in Newton's lenses, with the same colour employed by Schwerd in the above experiment, is found to be about $\frac{1}{160000}$ of an inch. This thickness we know has to be doubled to give the retardation, which gives us $\frac{1}{80000}$ of an inch for a *retardation* that causes a bright ring. Here then is an apparent discrepancy; for according to our calculation with the slit, $\frac{1}{80000}$ of an inch should only be *half* a wave, and the ring ought to be *black*. One or other of the reflected rays is *half a wave out*, or is in the contrary phase to what the mere retardation produces.

118. **Change of Phase in Reflection from a Rarer Medium.**—But on careful consideration this apparent contradiction proves the truth of the theory; since we perceive it ought to be so. We have seen that waves involve periods and phases even more essentially than lengths; and we have to consider what happens when a wave is reflected from a *denser* or a *rarer* medium respectively. Take for illustration, as simplest, our first example of wave motion, in a set of ivory balls. Let from A to B in Fig. 119 be large balls, and B to C much smaller ones, and let them be united together by an elastic cord *a c* through the centre of all. Then if we roll a ball up against A, the wave of *compression* is transmitted to B. There it throws off the ball D, which in turn passes on the wave through the smaller balls. But the small balls are not enough to take up *all the motion* as the large ones did; they are driven off more freely, in strict analogy to a wave encountering a *rarer medium*. The last ball D has therefore motion to spare, and *follows* the first small ball *e*, but slower and more feebly. In this it is however checked by the elastic cord, which instantly

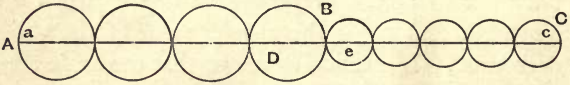

FIG. 119.—Dense and Rare Media.

pulls it back, or is rather pulled by it; and so the effect is really a *pull* upon the balls behind. In other words, the wave of compression is, *in the very moment and in the act* of reflection from the medium of less resistance, changed into a wave of extension. In other words again, it is converted into the opposite phase; or yet again, is thrown half a wave-length out of phase. If, however, we reverse the process, rolling the loose ball against the smaller row, so as to impart the impulse to *c*, it is not so. The last small ball *e* finds a *greater* obstruction to its motion instead of a less, and cannot therefore have any tendency to fly off; the reflected wave remains a wave of compression, as it was at the moment of impact.

Thus we see that when light is reflected from two surfaces of a film, one of which is the surface of a denser and the other of a rarer medium, the reflection which is of the latter character must be thrown half a wave-length, or half a phase, which is the same thing, out of its order. In a soap film it is the second surface; in the film of air the first surface. The result is that the retardation which, judging by *thickness alone*, would have retarded the ray from the second surface half a wave-length, is altered another half wave-length forward or back (it does not matter which, the alteration to the *opposite phase* of vibration being the point), and the two rays are brought into accordance, or give the bright ring. This measurement, therefore, now gives the same wave-length as the other.

The explanation can be easily subjected to experiment. If we use a top lens of very low density, and an under plate of great density, we can introduce between them a film of fluid of some *intermediate* density, as oil of sassafras. Both reflections then take place from a *denser* medium, and the retardation alone should come into play, without any other alteration of phase. Experiment fulfils this expectation to the letter.[1]

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[1] This explanation is taken in substance from Sir John Herschel, his popular exposition of it being the best I am acquainted with.

The apparent objection thus becomes a strong argument for the truth of the theory.

119. **Photographic Demonstrations of Interference.**—A similar reversal of phase occurs in reflection from many metallic surfaces, so that the surface becomes a nodal point, and causes interferences at successive nodes (corresponding to half a wave-length) between the *incident* and *reflected* rays. Wiener demonstrated this by photography in 1889. Placing a very thin homogeneous photographic film in contact with a silver surface, but very slightly inclined to it, and causing the light to impinge at an angle instead of normally, the distances between the nodes were so magnified that he obtained conspicuous interference bands on the photographic film, parallel of course to the line of intersection of the planes of the film and reflecting surface.

But still more striking confirmation—amounting in fact to absolute demonstration—of the literal reality of these interferences between waves, was furnished in 1891 by the beautiful photographic experiments of Professor Lippmann, of the Sorbonne. Carefully preparing thicker photographic films of homogeneous or non-granular structure (since such a structure, by dispersing the rays, destroys or impairs the phenomena), he backed the film by a bright reflecting surface of mercury, the film on its glass plate forming the side of a mercury trough. He reasoned, like Wiener, that any wave of definite length, passing through the film and then being reflected from the mercury, must occasion periodic interferences and reinforcements between the primary and reflected waves, at regular intervals corresponding with the half wave-length of the light employed. But with such an arrangement, reinforcement and extinction by interference produce respectively photographic action and non-action; and hence there ought to be a deposition from the silver-salt in successively recurring and equi-distant very thin layers, which should give by reflection the colour of the homogeneous light employed. This is found to be the case when proper precautions are taken; and many brilliant and nearly complete coloured photographs of the spectrum have been successfully produced in this manner,[1] forming thus an *absolute demonstration* of the wave-theory, and its phenomena of interferences. The experiment was entirely founded upon the theory, and has proved its truth to the letter.

120. **Hertz's Experiments.**—The other phenomena of interference are similarly capable of calculation. And the most complicated phenomena have so far corresponded with calculation in the most minute particulars. Perhaps the most far-reaching proof of the general phenomena of the undulatory theory, has been given by the classical experiments in electrical radiation worked out by Professor Hertz of Vienna in 1889, which are not unlikely to prove the most epochal discoveries of the nineteenth century. They not only provide demonstration of the undulatory hypothesis here considered, but equally so of all the fundamental features of the electro-magnetic theory of light formulated by the late lamented J. Clerk-Maxwell; and hold out hopes of carrying us ultimately some way into the physics of the ether itself. The very briefest outline of the nature of these experiments, so far as they bear upon our present subject, must however here suffice.

We have spoken hitherto of waves. What *is* a wave? We have referred to different *kinds* of waves—to waves in water, in air, in a row of balls, &c., &c. The phenomena of these differ materially, but we saw that the essence of the matter in all

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[1] Though in a sense this is true "photography in colours," it is not so in the ordinary sense, and it by no means follows that coloured photography from Nature will ever be attained by it, though he would be a bold man who would affirm the contrary. We have seen how *mixed* nearly all natural colours are; and it will easily be seen how the superposition of many different wave-lengths would destroy all the sharp precision of definite layers on which the photographic result depends, especially as all photographic action *spreads* a little in the plate itself. Also no sensitive salts have yet been found which respond equally to even the pure colours of the spectrum.

cases was this: that each successive particle of the medium passed through operations exactly similar to those of the preceding particle, a little later in time. That is the one point essential and common to all—in other words, a wave is some disturbance or change of state *periodic in space and time.* What is the nature of the disturbance in the ether which constitutes the physical basis of light, we do not yet positively know; but Clerk-Maxwell supposed it to be an *electric* disturbance, and found confirmation for his hypothesis in the fact, that the known velocity of propagation of an electric disturbance, and of light, were one and the same. It followed, however, that light ought to be stopped by conductors, which is the fact; and that insulators should be transparent, which latter was supposed to be contradicted by fact. If this latter difficulty were cleared up, it was comparatively easy to conceive how a wave of electrical disturbance might be propagated. The ether must possess, in regard to electricity, two qualities answering to what we call *elasticity* and *inertia.* Then a state of electric *stress* would correspond to the bending aside and holding by a detent of a steel spring. An electric *discharge* would correspond to the release of that spring; and the electric *inertia* of the ether would give the discharge such momentum as to carry it beyond the neutral point, and create a stress of the opposite kind; which would again be discharged, so keeping up an alternating or oscillating discharge. Such an oscillating discharge might be propagated as Light.

We know as a fact that there is this electric inertia, causing momentum, overplus, and recoil in discharges. If we cut a wire carrying a current round an electro-magnet, the momentum of the current carries a spark across the interval; and it has long been known that the discharge of a Leyden jar consists of numerous oscillations, which Professor O. Lodge has, by increasing the "capacity" of the apparatus, rendered so slow as to be made visible by a rotating mirror. But while such discharges cause sparks, and these sparks in a sense give "light," of the propagation in space *of the oscillation itself*, as a wave identical in character with light, there was till recently no proof.

This proof was Hertz's great step, and was afforded by the simplest means, viz., by providing a second sparking apparatus whose period was *synchronous* with the primary oscillation. This is very readily done by adjusting the "capacity"; then an apparatus so "tuned," as it were, acts as a "resonator" to the primary oscillation, and reproduces it, just as a tuning-fork in unison responds to another set in vibration. The next step was to increase the oscillations of the discharge in number and frequency, which was done by connecting the wires of an induction-coil to two small cylinders with sparking knobs set in line, and separated by a small interval. By this means oscillations were produced as rapid as 300 millions per second, which by calculation must produce (at the velocity of light) waves about a yard long.

Such waves as these—the shortest in length and period it is yet found possible to produce in this way—are still, of course, far too long and slow to be visible. (The spark is of course visible, but that is not what we are concerned with; what we want to get at is the *propagation of the oscillatory discharge* to a distance in space.) But by the "resonator" Hertz provided an electrical eye, as it were, which perceives the state of things many yards away, and by this aid he has demonstrated that the oscillatory discharge *is* propagated, and that such electrical waves *reproduce all the phenomena of light* with the utmost exactness. They reach the "resonator" with the same velocity as light. They are reflected, and brought again to a focus by parabolic mirrors. Using a large prism of pitch, with faces a yard square, they were found to be refracted; and pitch, wood, and other semi-insulators, opaque to visible light, are perfectly transparent to these longer waves, thus triumphantly verifying Clerk-Maxwell's hypothesis, and showing yet again that transparency and absorption are entirely questions of wave-length as compared with molecular constitution (§ 92). On the other hand, these electrical waves are reflected by metals. Lastly, by reflecting them back from sheets of metal, nodes of interference are produced (easily located by adjusting the resonator) which are precisely similar in all but the space between them (corresponding with the wave-length) to the nodes demonstrated by the photographic experiments of Professor Lippman (§ 119).

The rapidity already obtained in the oscillations of discharge, has been gained by the use of smaller and smaller oscillators. With these we have arrived at waves approximately three feet long; but the longest *visible* waves are only about $\frac{1}{36000}$ of an inch! To get such, we must conceive still smaller and smaller oscillators; but we should then find ourselves approaching in size the molecules of bodies. There is reason to believe that such oscillation of discharges between molecules, is just what happens when light is produced.[1]

121. **Size of Matter Molecules.**—I am not willing to conclude this chapter, without some explanation of the manner in which the dimensions of light-waves throw light upon the dimensions of the molecules of Matter itself. We are forced to conceive of Matter as consisting of detached molecules, or separate very small portions, on account of the enormous power of expansion which all matter possesses when heated. Moreover, while water and alcohol expand as one to three in the liquid form, for the same increase of temperature; in vapour they expand *in the same ratio*,[2] which we can only account for on the supposition that the molecules are now at enormously greater distances, so that their *special* action on one another has ceased, and they only obey the general laws of gases

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[1] Even as these pages are passing through the press, strong confirmation of this view has been given by the wonderful experiments of Nikola Tesla concerning the various effects of rapidly alternating currents of high potential. These currents no longer give shocks, while some of their phenomena closely resemble flames.

[2] About $\frac{1}{490}$ for each rise of 1° Fahrenheit.

exposed to heat. We are therefore confronted with these detached Molecules of Matter; and some of the questions physicists are now investigating, are concerning the probable size and other properties and relations of these molecules.

Now on the first of these questions the measurements we obtained of our light-waves throw very considerable light. First, the molecules must be considerably less than those waves in their dimensions, or they would be at least partially visible with the powerful microscopes we now possess. Nobert's test-lines of 112,000 to the inch—half the dimensions of a blue wave—were resolved in America by Dr. Woodward. Moreover, in many transparent bodies at least, as the waves pass through amongst the molecules without being very sensibly destroyed or affected, this is another proof that such waves are large in proportion; since they plainly are not split up amongst them, but as it were *surge* grandly over them, with little resistance. And yet, secondly, the molecules cannot be *infinitely* less relatively—or, shall we say, tremendously less; because if they were, it is easy to see that a difference in the waves of one half (we may take red light as $\frac{1}{38000}$ and violet as $\frac{1}{62000}$ of an inch) could not so profoundly affect the phenomena as it does. To use an illustration I have seen somewhere, sawdust would show no perceptible difference in effect upon water waves thirty feet and fifty feet apart; but logs of wood probably would. All this is indefinite, and yet it does give us a notion of what physicists call the class or *order* of magnitudes involved; and from some other considerations of this kind which cannot be given here,[1] it has been argued with very great probability that the average distance from molecule to molecule can hardly be more than a thousandth part, and hardly less than one ten-thousandth part, of the average length of a wave.

Very analogous deductions may be drawn from the phe-

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[1] Many of them are discussed towards the end of Tait's *Recent Advance in Physical Science* (Macmillan and Co.).

nomena of a soap film. With a good solution, if a film is stretched upon a ring as in Fig. 103, and carefully observed, after a while coloured bands cease to form, and a large white patch appears, answering to the first bright ring. This we know (§ 118) to be a thickness of *one-fourth* of a wave-length. But after this comes a patch of very dark grey, often called black.[1] Now the peculiarity about this is, that the boundary edge is perfectly sharp, as if cut with scissors! *It is not so with Newton's lenses, where the diminution of thickness is gradual;* and the only conclusion is, that in the soap-film there is some sudden change in the thickness, and therefore physical constitution of the film. As to the thickness, it cannot be *nearly* one-fourth of a wave-lengh, or a considerable portion of light would be reflected. It must be as compared with the wave-length practically *nil*, for either (1) the two reflecting surfaces are so close that the retardation is practically nothing, and discordance is produced solely by the half-wave difference of phase due to the denser medium; or (2) the film is so thin that the air on both sides is in optical contact and there is no reflection at all. Obviously the first supposition must be the true one; and it is very easy to see that if the film exceeded in thickness *one-fortieth* of a wave-length, we must have some traces of colour. We have here, then, apparently an abrupt transition from $\frac{1}{160,000}$ of an inch to something almost certainly not greater than $\frac{1}{2,000,000}$ of an inch;[2] and it is difficult

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[1] It is often stated that this grey only comes in patches, and that the film almost immediately bursts. With solutions made as described on page 154, I have had half the film remain of the dark grey for hours.

[2] Three years before the above was written, Dr. Dewar had estimated the thickness of the grey at $\frac{1}{1,000,000}$ of an inch. I think it best to repeat the reasoning which led me in 1882 to estimate the thickness at less than half that. Since then Professors Reinold and Rücker have proved, by most rigid experiments on two distinct lines which agree in their results—by measuring the electrical resistance, and, secondly, the retardation caused in a ray of light by passing through a definite number of films—that the thickness is in actual fact about $\frac{1}{2,500,000}$ of an inch.

not to believe that this must be due to some peculiar change in the physical *plan*, or constitution of the film; which again must almost certainly be in some simple numerical relation with the size of the molecules. And as we know that the mechanical equivalent of the heat required to vaporise a grain of water would not be sufficient (according to the law of capillary attraction) to reduce it to a thickness of $\frac{1}{500,000,000}$ of an inch, and therefore at that thickness the molecules could no longer hold together, but would separate in vapour, we seem to have here two outside limits between which the size of the molecules, or rather the distances between their centres, *must* lie.[1]

Finally, however, we can hardly suppose that a film only one molecule thick would hold together at all. We must therefore multiply the lesser limit by some figure, and we shall be within the mark in estimating the molecules in the film's thickness at from 3 to 5. Even this low figure brings the limits of measurement for the molecules of this form of matter as something like $\frac{1}{6,000,000}$ of an inch for the greatest possible distance between the centres and $\frac{1}{250,000,000}$ to $\frac{1}{100,000,000}$ (according to the multiplier we assume) for the least distance.

It is remarkable that several other lines of investigation lead to similar conclusions; but they need not be mentioned here. Only the merest outlines of the optical argument have been given; but these will suffice to show how Light is still, in another sense, a Revealer of those minute elements which can never be seen by mortal eyes.

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[1] Sir William Thomson believes that the molecules of gas cannot exceed $\frac{1}{50,000,000}$ of an inch; and Mr. Sorby estimates various molecules as probably from $\frac{1}{40,000,000}$ to $\frac{1}{160,000,000}$ of an inch.

APPENDIX TO CHAPTER IX.

Diffraction in the Microscope.

The phenomena of diffraction described in this chapter have a very important bearing upon microscopical investigation, and especially upon the advantage of increased angular "aperture" in microscopic objectives. That the increased angle obtainable by immersing object and objective in a fluid, instead of observing the object in air, gave marvellously increased powers of delineation, had long been known; but so long as this was supposed to be due merely to greater illumination, or the collection of a larger pencil of light from the object, it could not be satisfactorily accounted for. At length Professor Abbe pointed out the true nature of the advantage gained, and the matter was soon demonstrated by ingenious experiments devised by himself, Mr. Stephenson, and Mr. Frank Crisp, a full account of which may be found in the *Journal of the Royal Microscopical Society.* The following brief explanation is condensed from Mr. Crisp's lucid summmary of the subject in that journal for April, 1881, to which I am also indebted for the diagrams by which it is illustrated.

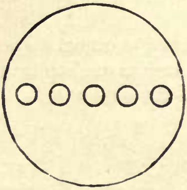

FIG. 120.

It will be understood, from the phenomena of "gratings" already investigated, that if between the reflecting mirror and the stage of the microscope we interpose a very small opening in a diaphragm, and on the stage lay a "grating" of ruled lines, on removing the eye-piece and looking down the tube we observe a series of images of the aperture like Fig. 120, circular in homogeneous light, but the outer ones consisting of spectra in white light. The small pencil admitted through the diaphragm is "diffracted," just as we have already found. We next lay upon the stage a slide such as Fig. 121, consisting of both wide and narrow lines ruled on glass. Removing the eye-piece as before, we have of course, on looking down the tube, the appearance presented in Fig. 122, the coarse lines

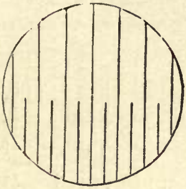
FIG. 121.

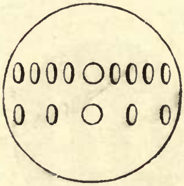
FIG. 122.

giving diffraction spectra twice as close and numerous as those caused by the fine lines. The reason for this we have already seen (§ 117); the present point is, what influence these diffracted rays have upon the image, and it is here that the experiments referred to are so important and interesting.

First of all, by a diaphragm at the back of the objective such as that in Fig. 123, let us cover up *all* the diffraction spectra, allowing only the direct, or central white pencil, to reach the conjugate focus, or image-point. On replacing the eye-piece,

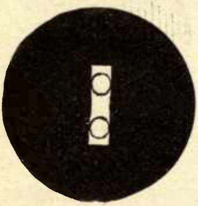
FIG. 123.

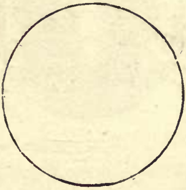
FIG. 124.

all the fine ruling has disappeared, leaving only the general outline of the object, as in Fig. 124. By suppressing the diffracted rays, therefore, fine detail or "structure" of an object is *obliterated.*

Secondly, let us adjust behind the objective a diaphragm like Fig. 125, which allows all the lower spectra in Fig. 122 to pass to the image-point, but suppresses every alternate spectrum of the upper set, diffracted by the coarse lines. The image now appears as in Fig. 126, the upper set of lines to all appearance being identical with the lower set. Precisely in the same way, if we substitute a diaphragm like Fig. 127, stopping off yet another half of the alternate spectra, the lines are again apparently doubled, and we "see" Fig. 128, though the actual object remains the same. In these experiments therefore, while retaining the central pencil of light throughout, we have *created* apparent detail or structure in the object by suppressing certain of the spectra.

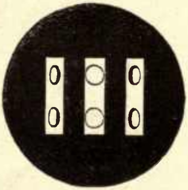
FIG. 125.

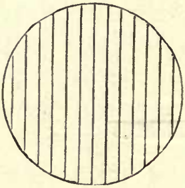
FIG. 126.

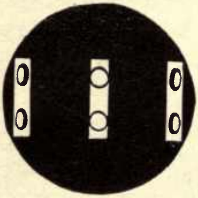
FIG. 127

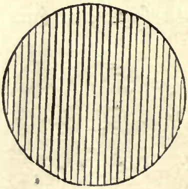
FIG. 128.

Still further, however, let us take a slide which when magnified resembles Fig. 129, or a "crossed grating." We get with this, from the small aperture, rectangular spectra somewhat like

Fig. 130; but these also cause *diagonal* spectra by their mutual diffraction of one another, as described in §§ 114, 116. Constructing a diaphragm like Fig. 131, which allows

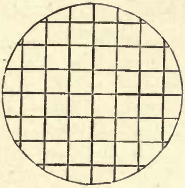

FIG. 129.

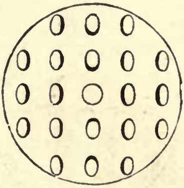

FIG. 130.

only the central pencil and two of these diagonal spectra to pass, the vertical and horizontal lines of the object have vanished, to be replaced by Fig. 132. This experiment is

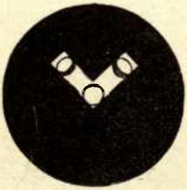

FIG. 131.

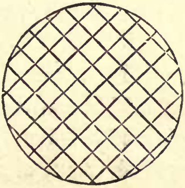

FIG. 132.

troublesome, the diaphragm having to be prepared with extreme care; but the results deduced from theory have been rigorously verified.

Now the microscopic student knows that many objects, by their minute and regularly recurring "structure," cannot fail to give, and do give, strong diffractive effects. The well-known *Pleurosigma angulatum* will serve as an example of the practical effect of the foregoing considerations. It gives three sets of diffraction spectra arranged as in Fig. 133. As each set is produced by something resembling alternations of structure at right angles to it, the three sets of lines in the object must be arranged *mainly* as in Fig. 134; but it will be obvious from what has gone before, that by selecting different sets of spectra, with or without the central beam, the apparent images will differ widely. It is also manifest that *all* these images cannot represent the true structure. If, however, we have the characteristic spectra, and their position and relative intensity can be calculated, then the resultant image can also be calculated; and *so far* as all the spectra are included, it will represent the real object.

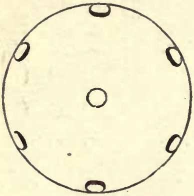

FIG. 133.

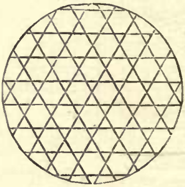

FIG 134.

The general conclusion is, therefore, that we have no true image of an object whose structure is sufficiently fine to give strong diffractive effects, unless *all* the diffracted rays, or rather, perhaps, all the truly characteristic sets of spectra, are collected; and the image will more or less resemble the object, in proportion as the spectra are all collected, or at least sufficient of these characteristic spectra. As we have found before (§ 117) that the finer the grating, the more widely deflected are the diffracted spectra, we can readily understand how, as regards minute structure especially, collection of the widest possible angular field of rays from the object is a point of the utmost importance for correct *delineation*, quite irrespective of greater *illumination;* and it is in this respect that immersion objectives have such an enormous advantage.

Of course these considerations only apply to structure of a certain degree of minuteness. With more coarseness, all the diffracted spectra which are visible may be collected by a moderate angle. But when we reach a certain fineness, it will be seen that the image in a microscope of small angular aperture can be no true representation of the object at all, but is due to peculiar selective conditions. This may be well shown by an experiment with *Amphipleura pellucida.* With a homogeneous-immersion objective of large aperture, focus the object under an illumination so oblique as to show up all the lines clearly. Then remove the eye-piece as in previous experiments; and placing the eye near the conjugate focus or image-point of the objective, the direct beam will be seen to emerge obliquely as a bright spot; while on the other side of the field, and close to its margin, will be seen more or less of the inner portion of the *first diffraction spectrum.* (Fig. 135.) Only a portion of *one* spectrum, observe; and that so near the margin that it must be lost with any objective of much less angle. If now a small bit of paper be adjusted on the back lens of the objective so as to stop this spectrum and no more, the illumination is diminished by an almost infinitesimal portion, and the diatom is still visible, apparently as brightly illuminated as before. But the characteristic *striation*, which caused, and was therefore imaged by, the diffracted light, is gone, just in the same manner as was demonstrated in Figs. 123 and 124.

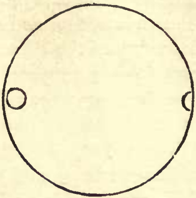

FIG. 135.

NOTE.

I prefer still to represent the Abbe theory in its earlier, moderate, and demonstrably accurate form, rather than in the extreme and (as I consider) wholly inaccurate development which has been given to it since the first edition of this work appeared. It is in this earlier form that Professor Abbe's brilliant discoveries will remain, I believe, ever associated with his name; that they pointed the way to marvellous advances in microscopic optics, which are also chiefly due to his hands; and that they still point the way, not illusively, but with well-grounded hope, to nearer and nearer approaches towards an ideal of perfection; whilst his later and extreme views logically imply the worthlessness of the work he has himself done, and confront the optician with a *dictum* of blank despair. As the *Journal* of the R.M.S. has practically suppressed any further discussion of Professor Abbe's views, it may be well to add a few words respecting the distinctions to be drawn, in my opinion, between their earlier and later form, and the reasons (as they appear to me, from considerable study of diffraction phenomena) for making such marked discrimination between them. This seems the more advisable, because it has been repeatedly stated that the theory here questioned has "been demonstrated by mathematical analysis." As all physicists are aware, no theory of the kind *can* be demonstrated by mathematical analysis, which solely deals with quantities or relations or functions already postulated or proved by experiment. The theory itself must stand or fall by its consonance or otherwise with ascertained physical facts; and the following remarks are made solely from this point of view.

The different nature of Abbe's later theory is easily made clear. The reasoning and experiments briefly summarized in the text above, imply the great advantage, and as regards the image of minute periodic structure the necessity, of the microscopic object-glass embracing a wide-angled cone of rays from each point in the object; and they further imply, that with a wide cone of rays (other things being equal) we may expect greater truth of image. But in a much more recent paper (*Journal* R.M.S., 1889, p. 723), Professor Abbe, if his argument be admitted, utterly demolishes a large part of this fabric. The whole paper is directed against the value of wide-angled cones, on the alleged ground that every ray (or infinitely small pencil of rays) of which the illuminating cone consists, causes its own "fan" of diffraction-spectra, owing to the different obliquities of these original pencils. Of such fans he then alleges: "These various elementary diffraction-pencils, mingled together within the objective, produce images of the object *quite separately*. Every single elementary pencil gives rise to its own image, the rays of different elementary pencils *being unable to co-operate*." Hence he concludes: "The resulting image produced by means of a broad illuminating beam [by which he means, as he has explained, a wide-angled cone] is always a mixture of a multitude of partial images, which are more or less different, and dissimilar to the object itself. There is not the least rational ground, nor any experimental proof, for the expectation that this mixture should come nearer to a strictly correct projection of the object (be less dissimilar to the latter) than that image which is projected by means of a narrow axial illuminating pencil."

As regards "experimental proof" space forbids discussion here; but the converse of the above proposition in that respect has been absolutely demonstrated by Mr. E. M. Nelson, in the *Journal of the Quekett Club* for July, 1890. Ample experimental proof will be found there detailed, that a wide cone does give true images where a narrow cone gives false images, and that Abbe's earlier theory is practically correct, as against his later one. Here only a few remarks can be made in attempt to show that there is every "rational ground for the expectation" that such would be the case.

We have seen already (§§ 15, 42) that a visible image is produced, when upon any point of a screen or other image-plane there are re-collected rays diverging from one point in an object, and when no other rays reach that point of the screen. In the microscope, the diverging pencils are thus re-converged by a lens, and the result is called a dioptric image in all other similar cases. Professor Abbe, however, laid down the proposition even in his earlier statements, that the images due to diffraction-spectra were not dioptrically formed, but due to *interferences* of the diffracted rays. This proposition appears to me fundamentally erroneous, and to have naturally led ultimately to the further conclusions above. Consideration of the phenomena will, I think, make it clear that the diffraction image, so far as it is a real image at all, is *dioptrically formed* precisely as is the image formed by all other rays.

The diffraction-spectra due to very fine striations in an object are themselves due to periodic selective interferences, as we have seen in the text of this chapter. Not only so, but in simple fact *all rays of light*, in themselves, are phenomena resulting from interferences precisely analogous to diffraction, as very briefly explained in § 67. Confining ourselves however to the apparently simpler phenomena of diffraction, and taking the experiment with *P. angulatum* above (Fig. 133), every stria in the object sends to the same point on a screen its contribution to the effect, adding to the brilliance of *the same band* of light of any given wave-length; whilst on the other hand interferences destroy the light in the dark bands. But in seeking a microscopic image, the arrangements differ radically from those described above. In place of a small aperture beneath the stage, we have a small source of light carefully focussed upon the diatom by the condenser. This focussing of the light itself implies that the luminous rays, diverging afresh from the condenser's focal point, are *identical in path* with the image-forming rays proceeding from the object as in § 42. The object thus appears to emit the rays upon its own account. This is readily understood and admitted, as regards objects seen by scattered reflection, but seems to be practically forgotten as regards transparent objects seen through the microscope; that it is equally true of them also, however, is well shown in "dark-ground illumination," where all direct light is excluded from the objective, and the object is seen brilliantly illuminated by the rays reflected or refracted or diffracted from the points of the object, and by these rays alone.

This being so, however, it does not matter in the least, so far as the dioptric character of the image is concerned, *how* the rays of light are caused to diverge from any point in the object. Whether they scatter by reflection, or scatter by refraction, or scatter by diffraction, the fact remains that they *diverge from the one point;* as such a diverging pencil of rays the lens collects them, and converges them again to the conjugate focus. At that focus there must be an image, and the only true image; and that image is a *dioptric* image, though partly due to diffracted rays. The first passage quoted above is therefore contrary to fact in both sentences. The "various elementary diffraction-pencils" do *not* "produce images of the object quite separately": they do not of themselves produce any images at all, and without the objective never would do so. The spectra diverge from the object, not from or in the lens; and it is necessary for the lens to *re-converge* them to get an image, just as all other diverging rays are re-converged to the conjugate focal point. So far from being "unable to co-operate," an experiment properly carried out proves that they can and do co-operate; and that a perfect lens, to the limit of its aperture, will bring every ray diverging from any point in the object, *however caused so to diverge*, to one and the same image, which is a dioptric image as regards every ray thus re-converged by a lens.

This reasoning only holds good in its fulness, when the luminous point of emission, and the point of emission from the object itself, practically coincide. Hence coincidence of image-point for the direct and the diffracted rays must largely depend upon a small source of light being accurately focused upon the object; and it will be limited to the aplanatic aperture or cone of the condenser. That these conditions are necessary to what is commonly called a "critical" image, is well known; and the fact is a strong confirmation of the view here expressed.

There is further a very simple optical principle which gives strong "rational ground for the expectation" that, as Professor Abbe formerly taught, the image will be a true image so far as all its elements are grasped by the lens. It is the simple optical principle of *reversibility*—the fact that if we consider the image as an object, rays traced from it backwards must give us an image exactly resembling the object. Why it is, that if a striation causes diffraction-fans, we must utilize these fans of rays if we are to truly image the striation, we do not fully know: yet it seems reasonable to suppose that, in face of the fundamental connection between minute striation and such separation of the rays into diffraction-fans, it should be so. One reason may be, that wherever striation is uniform or periodic, every element in it combines to intensify the phenomena—the light that images a single line in a grating, is contributed by rays from *every other line*, and intense in proportion to their number; the bearing of which upon the question of visibility is readily seen. Apart from any lens or question of aperture, the greater the number of lines in a grating the greater its power of "resolution;" and the same law holds good as regards the mere thickness of glass traversed by the rays through a dispersive prism. That such is the whole truth, is not however suggested. All here insisted upon is the simple fact—for it is a fact—that every ray diverging from a point of the object is converged *dioptrically* (so far as the lens is perfectly corrected and embraces the pencil) to the conjugate focus, and that here alone can be a true image.

The student who has experimented with perforated cards in the manner described in § 114, will not be at a loss to understand Professor Abbe's disbelief in the truth of any results from diffraction pencils. He will have learnt from those experiments how *interferences* of pencils from the numerous apertures, do also produce the most surprising changes of pattern and appearance, as the focus of the objective is altered. Such patterns are readily thrown upon the screen ; and if a single card or plate be used, the phenomena will very closely resemble those of a diatom in the microscope. But these are mere interference *fringes*, not images in any sense. There is still one true image to be got, and one only ; and it is in the plane where the diverging diffraction-fans are truly focused by the lens. One has only to consider how subtle a thing, compared with this rough focusing, is the focusing of a diatom of 50,000 striations per inch under high power, to understand all the baffling microscopic phenomena.

But there are further the imperfections of the microscopic objective and condenser to consider, and especially in the one point which Professor Abbe has himself, in the celebrated lenses constructed on his formulæ, most markedly disregarded. That point is *flatness of field.* It is generally held that this quality, and that of definition, are to some extent incompatible. Practically it has heretofore been considered so, with large apertures ; and Professor Abbe's own lenses have accordingly sacrificed the one point largely to the other. But it is easy to see that flatness of field—the requirement that an object in one plane should be truly imaged in one plane—is of vital importance as regards diffraction pencils caused by minute periodic structure. The very few elements in the centre of the field may be truly focused, and so far all seems favourable to a true image. We shall indeed get such of a minute *bacterium* or *flagellum*, and probably even of a small portion broken off separately, containing only two or three elements of a diatom structure. But with an entire diatom containing many elements the rays diffracted from more circumferential elements of the striation, are not focused by a lens whose field is concave instead of plane. Now with *periodic* structures, rays from these outer striations which are not in focus, not only go to form their own image, (which we may be willing to neglect) but *also go to impair by interference the image of the centre striations also.* They are not in true focus there either ; and so we may get a false interference "pattern" instead of a true image. Different zones in the area of the lens may also have different foci, and very often have such. Though very difficult to remedy, this latter fault is however well understood ; but the necessity, so far as avoiding unfocused interference "patterns" and getting one true dioptric "image" is concerned, of the *outer elements being in true focus, even to secure the inner elements themselves being only formed by truly-focused rays*, does not seem to have been acknowledged, and is a point in which the optician has to learn from the physicist.

The condenser also plays a most important part in the result, and Professor Abbe's old chromatic form, which has been so largely used in problems of high aperture, is about the least capable of giving any true image at all, that could possibly be constructed. It is highly chromatic, and is incapable of any true aplanatic focus. But every ray from the lamp-flame not truly focused upon the striated structure, cannot be truly converged to an image, and by false "crossing" must produce interferences with other rays.

To come to a practical conclusion: the task thus set before the microscopic optician is doubtless one of tremendous difficulty. If he is to attain a true image of a minute periodic structure, he *must* combine perfect flatness of field in his lens with perfect corrections in other respects, and he must produce a perfectly aplanatic condenser. This perfect ideal may be unattainable, though Professor Abbe has himself done so much that we may reasonably hope for much more. But so far as attained, an unmistakable image, which alone can be beyond doubt accurately focused, will assuredly be obtained with it, true in proportion as all the elements are gathered in. That very much advance may be made in this direction, is shown by the recent beautiful apochromatic lenses of Powell and Lealand, which, without the slightest loss in definition, have attained a much greater degree than formerly of flatness in field. This fact I myself proved by exhaustive screen tests; and it is noteworthy that Dr. Dallinger, many months afterwards, from tests entirely different in character of the very same power (⅛ inch) so tested by me, pronounced it a lens to which he had seen, from his own practical working point of view, "no successful rival." In any dozen lenses, there are moreover some much flatter in field than others, without being at all defective in other respects. There are ample proofs that, with the aid of fluorite and its wonderfully low figures of refraction and dispersion, the real importance of this factor has only to be adequately recognised, instead of being ignored, for great advances in performance to be made. The optician may at least work on, with all the hopes first aroused by Abbe's classical discoveries; not checked by the negation to all his efforts implied in the paper above cited.

CHAPTER X

DOUBLE REFRACTION AND POLARISATION

Double Refraction—Huygens's Experiment of Reduplicating Images—Polarisation—Polarisers, Analysers, and Polariscopes—Phenomena of Tourmalines—Polarisation by Reflection and Refraction—What Polarisation implies—Analysis of Polarisation by Reflection and Refraction—The Polarising Angle—Direction of the Vibrations—Analysis of Polarisation by Double Refraction—Principal Planes—Extraordinary and Ordinary Wave-Shells in Doubly-Refracting Crystals—Action of the Tourmalines—Appendix: Vibrations of Common Light.

In dealing with light hitherto, we have found it reflected, or otherwise behaving according to certain uniform laws which were not affected by the position or direction of the ray. We have now to examine phenomena in which that is not the case.

122. **Double Refraction.**—Place in the optical stage the smallest aperture that will show a bright spot upon the screen, and in front of the nozzle hold a piece three or four inches long of the clear mineral called Iceland spar, which crystallises in the form of a rhombohedron, as shown in Fig. 136. There appear perceptibly *two* images, separated by a slight interval; and if the spar is turned round pretty equally, it is seen that one image rotates round the other. It is plain that the single

pencil from the lantern A B (Fig. 137) is, in passing through the spar, divided into two, B C and B D; and equally clear that if one of these rays is refracted in the plane of incidence, and

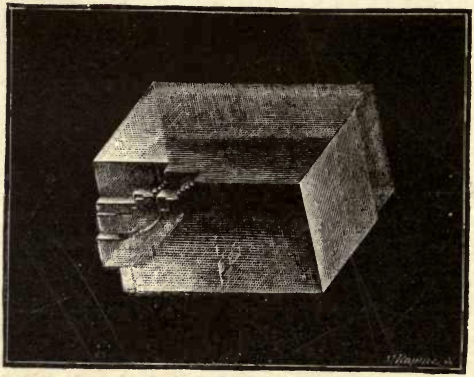

FIG. 136.—Iceland Spar or Calcite.

according to the law of sines, the other in some positions cannot be. It is also obvious that somehow or other the indices of refraction (§ 33) must differ in the two rays.

Large pieces of spar are clumsy, however, and give little separation, as both rays resume parallelism (C E, D F) when

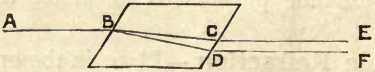

FIG. 137.—Double Refraction.

they emerge from it. But as we have two indices of refraction in certain positions, if we cut a prism of the spar, with its refracting edge in a proper position, the angular deviation will continue after the two rays emerge, and the separation increases with the distance. The dispersion of such a prism is easily achromatised, or nearly so, with a reversed prism of glass,[1] and a small bit of spar thus treated gives us a wide separation. We shall suppose *two* such prisms, A and B (Fig. 138), mounted in cork, and so fitted that the brass tube containing the first rotates on the nozzle at N, while the second, B, rotates in the first, with a space, S, between them, through which, by slits in the sides of the mounting tube, a slide an inch wide can be inserted. Two double-image prisms thus fitted are usually called a "Huygens's apparatus."

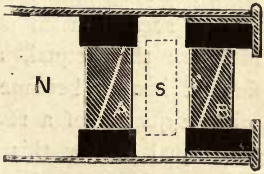

FIG. 138.—Huygens's Apparatus for the Lantern.

123. **Huygens's Experiment.**—We can now use a larger aperture. Place one, $\frac{1}{4}$ inch in diameter, in the optical stage, and focus the image; on placing one prism on the nozzle and rotating it, one image is seen to revolve round the other, but no difference in brightness or otherwise is observed. Let A (Fig. 139) represent these two original images. Add the second prism in front of the first, however; and keeping the first immovable (say with its two images vertically disposed), rotate the other in front of it. Starting with both prisms in the same position, two images still appear, only at double the distance, B, showing that each ray from the first prism suffers no further division, but is only further bent in passing through

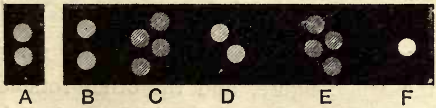

FIG. 139.—Huygens's Experiment.

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[1] A better plan is to make both prisms of spar, cut in two directions at right angles with each other, on a plan devised by Dr. Wollaston. This gives better chromatic correction, and doubles the separation of the images.

the second. But directly the front prism is rotated in the least degree, *four* images appear; each pair being of unequal brightness, however, until one-eighth of a revolution has been made, or the second prism is at an angle of 45° with the first; all four are then equal, as at C. Proceeding, what were the faintest images become the brightest, and *vice versâ*, until when a quarter of a revolution is reached there are again but *two* equal images, this time, however, placed at an angle of 45° from the perpendicular on the screen, D. Still proceeding, the same stages are gone through reversed; but on reaching the half revolution, if both prisms are of equal separating power, there is but *one* image, F, into which all four have merged. The successive phenomena are represented in Fig. 139, and are of course reversed through a further half revolution back to the first position.

The student will do well to examine these phenomena more in detail, if possible, which he can easily do without any other apparatus than two small rhombs the size of Fig. 140, if he does not possess two such prisms as described. They can either be laid on a sheet of paper with one round black spot, or held against the window over a pin-hole pricked in a black card. Let the under rhomb be kept in the same position as shown by the white figure, and the other rotated over it as shown by the shaded figure. It will first of all be seen that with the single rhomb, if so cut that the sides are of equal length, the line joining the two images is always parallel to the short diagonal. The same will also be noticed of the reduplication of the images; and the details of the diagram will enable the successive modifications to be accurately traced, and show all that takes place. (The *white* spots represent a total extinction of the image.)

124. **Polarisation of Light.**—It is manifest that the pencils of light which have passed through the first piece or prism of Iceland spar, differ remarkably in some way from common light; and that the difference essentially consists in

this : that they behave differently according to which of their *sides* are presented to certain sides of the second prism. We have here an obvious analogy to the "polarity" of magnets and currents of electricity, which, though not strictly accurate, is sufficient to justify the term of "polarised" light.

125. **Polariser and Analyser.**—And the analogy goes farther. As we cannot detect magnetic polarity until we bring to our presumed magnet some other magnetic or diamagnetic substance, by whose attraction or repulsion we detect the magnetism ; so here, we could not *detect* any "polarisation" in our two pencils of light, until we subjected them to a *second* process similar to the first. This law holds good throughout the subject. A great deal of reflected and other light around us is, as we shall immediately find, really polarised ; but we cannot detect it to be so without subjecting it to some second

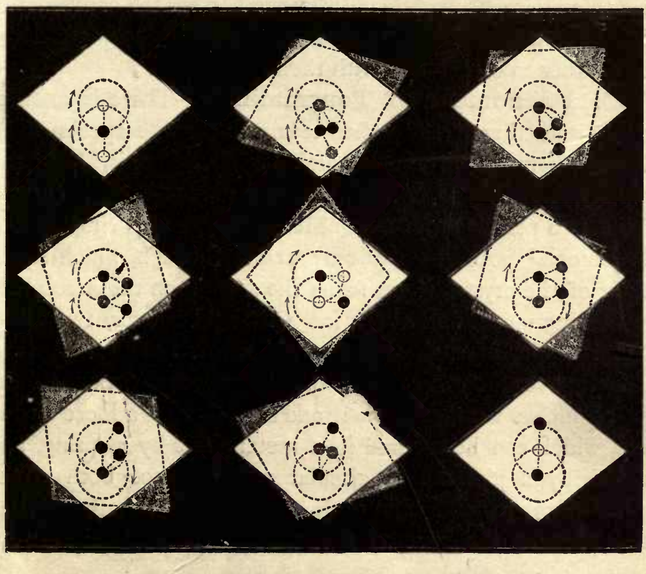

Fig. 140.—Analysis of Huygens's Experiment.

process, which of itself would polarise it were it not polarised already. If it is, such a further process at once *reveals* the already existing polarisation, and the apparatus so used is then called an "analyser." A polariser and analyser together form a "polariscope." Any one of the methods which are capable of polarising light, may be used equally to analyse light when polarised; whether it be the *same* process as polarised it or not, being a matter of complete indifference beyond the convenience of the operator. These methods are several, and we have now further to experiment with them.

126. **Phenomena of Tourmalines.**—There is another doubly refracting crystal called tourmaline, some specimens of which, when cut in slices parallel with the axis, have the property of rapidly absorbing, or being almost opaque to, one of the two pencils produced. Hence we greatly simplify the phenomena.[1] As one ray only passes through, which is the colour of the crystal, if we focus the slice upon the screen, we see nothing remarkable about it. Obtain, however, two slices of tourmaline, of such sizes and shapes that one can be seen distinctly over the other. Let one be mounted in one of the 4 × 2½ inches wooden frames, and the other on a loose disc of glass, which can be secured in a metal circle by a spring, and rotated by a pinion and circular rack.[2] Place both in the optical stage, parallel with each other, and focus; then rotate the front one: the successive appearances are as in Fig 141,

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[1] Two mistaken statements are often made about tourmalines. One is, that green ones are good polarisers. Some few are, but many are not, and far the best colours are the various shades of browns, or some which are a very pure purplish grey, and very little change the colour of objects seen through them. The other error is that tourmalines "polarise by absorption." All that the absorption does is to take up or stop one of the *already-polarised* rays due to double refraction; for if a very thin wedge be ground, at the thinnest edge both images can be distinguished.

[2] Such rotating frames, of the standard 4 inches by 2¼ inches size, can be purchased for a few shillings of any good London optician, and at least one is indispensable for many experiments.

When parallel, A, there is simply a rather deeper colour from the double thickness; when the movable one is rotated 45°, as at B, a considerable portion of light is stopped where both are superposed; when at right angles, C, no light whatever can get through—the screen there is black.

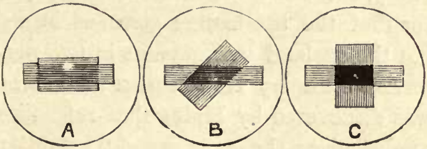

FIG. 141.—Two Tourmalines.

It is plain we have here the same phenomena as before, only simplified by the absorption of one of the two rays. To prove it, we remove the fixed tourmaline, leaving only the rotating one in the stage, and placing with it a circular aperture in a plate or card, just large enough to encircle the tourmaline. On the nozzle of the objective we place one only of the double-image prisms, which if of wide angle will quite separate the two circles of light with the tourmaline image in the centre; if the separation is not sufficient for this, remove the second lens from the objective, and insert at C, Fig. 1, a lengthening tube or adapter, about $2\frac{1}{4}$ inches long, which by reducing the size of the discs, but not their distance apart, will "clear" them on the screen. Adjust the prism so that the images stand horizontally, while the tourmaline stands vertically. One image transmits the light, the other is completely black (A, Fig. 142). Now rotate the tourmaline till it stands horizon-

FIG. 142.—Tourmaline and Double-Image Prism.

tally; the light image gradually becomes black, and *vice versâ*, (B) whilst in passing through the angle of 45°, both are alike and semi-opaque. Rotating next the prism, while the tourmaline is stationary, the same alternations are repeated. It is perfectly clear that the tourmaline gives us in a single pencil, precisely what the Iceland spar gave us in two pencils.

127. Polarisation by Reflection and Refraction.—In 1808 it was discovered by Malus that reflection from glass at certain angles gives the very same "polar" phenomena; and a few years later it was discovered that the refracted ray which passed through the glass had the same property. On a piece of board, B D (Fig. 143), as base, glue or screw two triangular side pieces, B C D, and fix between the hypothenuse edges of these, B C, ten or twelve plates of thin crown or plate glass, so that the angle A B C, is about 56°. It is evident that when laid on a table stand in front of the objective, a beam, E F, from the lantern will be partly reflected towards the ceiling as F G, and partly refracted and transmitted to the screen as F H. Adjust it thus: remove the double-image prism but leave the rotating tourmaline in the stage. On rotating the tourmaline, it will be found that when this is horizontal, the reflected image on the ceiling is bright, and when the tourmaline is vertical, black; and on looking at the screen we see that these effects, by the transmitted ray, are precisely reversed. And if we place an aperture in the stage without the tourmaline, and on the nozzle the double-image prism, we of course find on screen and ceiling reciprocally light and dark images of the

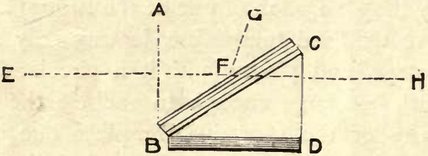

FIG. 143.—Glass Pile.

aperture, which change to the opposite character as the prism is rotated. Next lay the apparatus on its triangular side, and every image is precisely reversed. All through we have found similar phenomena; and if we use the pile of glass *first* (either as reflector or transmitter) and another pile of glass, or any of the other apparatus, after it, it is still the same; the beam of light when "polarised" by any one of these methods, behaves in opposite ways when "analysed" by any one of the methods, in positions at right angles with each other round the axis of the beam.

A single plate of glass is sufficient, when adjusted at the exact polarising angle, to polarise all the light that is reflected; and an equal quantity of polarised light is also transmitted through the plate. But this quantity being small, and in the case of the transmitted beam overpowered by the larger quantity of common light also transmitted, it is usual to employ a pile of at least a dozen plates. Even this does not polarise all transmitted light, but sufficiently increases the quantity of reflected light. Owing to inequalities in plates of glass, for accurate experiments it is sometimes necessary, when reflected light is employed, to employ only one plate of perfectly flat glass blackened at the back. At other than the angle of complete polarisation, a somewhat *less* quantity of light is polarised.

128. **Nature of Polarisation.**—The phenomena of double refraction and polarisation puzzled Huygens and Newton, for opposite reasons. Newton's notion of alternate "fits" could be made to account in some measure for polarisation, but not for double refraction. Huygens could not account for polarisation, but easily accounted for double refraction on the Undulatory Theory, even as then understood, when it was supposed the ether vibrations resembled those of sound-waves, or were propagated in the direction of the ray. We have seen that the retardation which causes refraction is most probably caused by *greater density* or *less elasticity* in the ether within the re-

fracting body; and Huygens had only to suppose a doubly-refracting crystal was less elastic in some directions than in others, to account for it, provided only the ether vibrations also were affected by these differences in the structure of matter. This, we have found from numerous experiments, is probable. But the theory as then understood failed to account for polarisation, which finally occasioned Young and Fresnel's great conception of *transverse* vibrations, by which everything is simply and perfectly accounted for.[1] Let it be supposed that common light consists of vibrations in all azimuths, but all perpendicular to the path of the ray, as at A, Fig 144. Whether vibration takes place in different azimuths simultaneously, or in succession, does not affect the reasoning.[2] Such a ray must behave indifferently as to its sides, whatever it meets with in its path. But let all these azimuths of vibration be "resolved" into *two* planes at right angles to each other, as at B,

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[1] Familiar as the conception is to us now, it is difficult to realise what a profound and tremendous revolution in scientific opinion it was, when first promulgated by Young and Fresnel in 1816 and 1817. To endow such a rare and subtle fluid as the ether with the most distinguishing property of a *solid*, was such a stupendous overturn of all previous notions about the Undulatory Theory, that Arago, who had up to that time shared and endorsed Fresnel's previous memoirs, shrank from such a step, and left Fresnel to bear the brunt of it alone. Fresnel related in 1821, that he himself hesitated to adopt it for a while, and states (see Whewell's *History of the Inductive Sciences*, vol. ii., p. 417) how "Mr. Young, more bold in his conjectures, and less confiding in the views of geometers, published it before me, though perhaps he thought it after me." Whewell goes on to relate, from information given him personally by Arago, how when Fresnel had pointed out that transverse vibration was the only possible way of translating the facts of polarisation into the Undulatory Theory, the elder Frenchman "protested that he had not courage to publish such a conception, and accordingly the second part of the Memoir was published in Fresnel's name alone." And yet, when Arago thus shrank from the new theory, he had received also a letter from Dr. Young, dated January 12, 1817, in which the same idea was suggested for the same reasons! Facts like these should not be lost sight of, for the sake of the instruction they convey to the student of science.

[2] See Appendix to this chapter.

where the top and bottom quadrants of A are supposed to be mainly resolved into C D,[1] and the others into E F; and suppose we can obtain either plane *separately;* for instance, the spar separates them somewhat as at C. Very plainly, such a fixed plane of vibration, on meeting reflecting and refracting surfaces, must behave very differently according as the *ends* or *whole course* of each path of vibration come in contact with the reflecting or refracting surface.

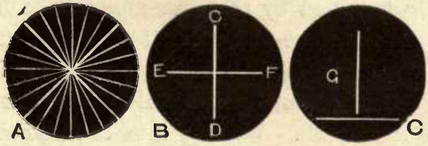

FIG. 144.—Nature of Polarisation.

129. **Analysis of Polarisation by Reflection and Refraction.**—It is even easy to see that reflection and refraction, of themselves, must tend towards this state of things. For tracing a ray whose transverse vibrations are in all azimuths, to an inclined surface, it is natural to suppose those vibrations which come in contact with that surface, or "kiss" it as it were, along their whole path, should be reflected in their integrity, while others must be seriously affected. A simple experiment confirms this supposition. It is supposed throughout the Undulatory Theory that we are dealing with actual physical realities—with actual physical atoms of some kind, vibrating with inconceivable rapidity in definite paths. Now, any *solid* small body thus moving in an orbit, with sufficient rapidity, produces on our sense of touch and in many

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[1] It results from very elementary principles of mechanics that if C D and E F are the only possible directions of vibration in a body, all vibrations in any other azimuth than one of the two must be resolved into both in varying proportions according to the angles. Near C D nearly all the motion is resolved into C D, and only a small portion into E F; while the vibrations in azimuths of 45° will be resolved equally into C D and E F. (*See* Fig. 170.)

other mechanical respects (and we are dealing with strictly mechanical effects here) the same effect as a solid occupying the dimensions of its path. If, for instance, the driver-stud in the driver-chuck of a lathe can be rotated with sufficient rapidity, it is in many respects mechanically equivalent to a solid *cylinder* bounded by the circumference of its circle of revolution. In the same way, a small sphere vibrating rapidly enough in a path perfectly straight, would produce effects similar to those of a small rod, equal to it in diameter and of length equal to its path. We may thus conceive of the front of a ray of light, supposing there are transverse rectilinear vibrations in all azimuths, as equivalent to a number of rods crossing the axis of the ray in all azimuths, as A, Fig. 144. Now let us consider these various rods, preserving their rectangular relation to the ray, obliquely projected against the surface of some retarding medium, such as we have considered refracting media to be.

We can predict the result theoretically; but we can, as regards *single* rods, representing single azimuths of vibration, subject the matter to experiment by the simple instrument shown in Fig. 145. Let there be hinged on a base-board, B A, at a pivot, a light frame C, pulled towards B by a strong spiral spring, S. On pulling it back and releasing it, the part C will

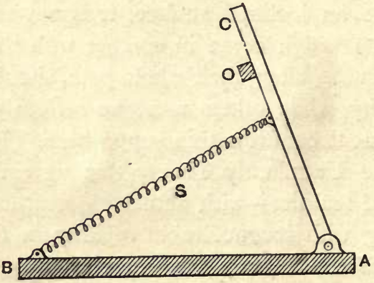

FIG. 145.—Catapult.

act as a kind of catapult, and project objects laid upon it with considerable velocity at any inclination with the horizon, determined by a stop or obstacle, O. Provide a few smooth rods of wood, as accurately circular as possible, of different diameters and weights (because the best rods for each projecting apparatus must be found by trial : as a rule rather heavy wood is best), and placing the instrument in front of a shallow bath of water, project the rods obliquely against the water. Let a horizontal rod be first so projected, so that the whole length strikes the water at the same moment. With a little practice it will be found that when the rod is projected pretty accurately, it is *reflected* from the water, as in Fig. 146, as boys play "ducks and drakes," or as a shot ricochets on the surface of the sea.[1] Now let A (Fig. 147) be the wave-lengths in a ray of light, the rod R will represent those vibrations which reach the retarding medium as at B ; and they are *reflected* to C. Lay next a rod *vertically* on the face of the catapult, so that the *end* strikes the surface of the water first, as at E (Fig. 147). Such a rod represents mechanically the vibration at right angles to the former ; and it will be found it is no longer reflected, but swung round in some such direction as F.

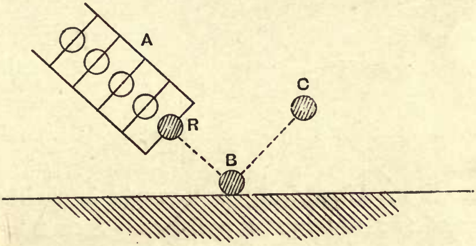

FIG. 146.—Reflected Rod.

But this is not all ; for attentive observation, even with this

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[1] The rods must strike the surface of the water at a considerably less angle than in Fig. 146.

rough and simple apparatus, will show that, in rods placed in intermediate positions, there is a sensible, visible tendency on meeting the water to *swing round* into one or other of the two positions we have examined. It follows that if we could project such a rod, without losing its energy, against surface

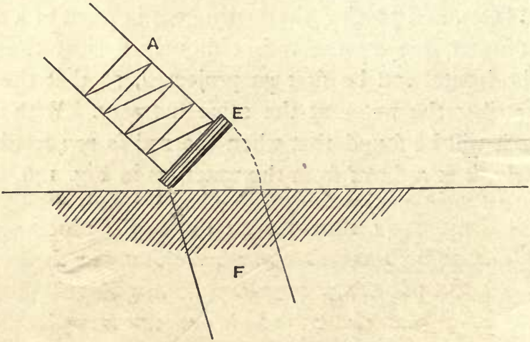

FIG. 147.—Refracted Rod.

after surface, it would gradually be brought into either one or other of these two rectangular positions. And this precisely accounts for what was long a difficulty, viz., the *gradually increasing* body of polarised light, as common light is reflected from, or transmitted through, a greater number of successive plates of glass.

130. **The Polarising Angle.**—Lastly, a very elementary knowledge of geometrical mechanics necessitates the clear perception that, according to this purely mechanical method of analysis, the amount of reflected and refracted light polarised in two rectangular planes, assuming the original beam to contain equal proportions of all azimuths, must be equal; and further, that the most favourable position for the operative surface, or that which must give from any surface the largest quantity of each kind of light, must be at an angle of 45°, at which angle alone an equal number of azimuths are affected in

each of the two directions, and at which alone the transmitted ray is at right angles to the reflected ray. Now, at first sight, this seems to be contradicted by the fact that the polarising angle of glass is not 45°, but about 56°, and that it varies with every transparent substance. But when examined this difficulty disappears; for Sir David Brewster discovered in 1815 the beautiful law shown in Fig. 148. Reference to the diagram of sines (Fig. 40) will show on mere inspection, that there must be a given angle of incidence, at which the ray, I R (Fig. 148), *reflected* from the refracting surface, at the same angle with the normal, N, as the incident ray, S, is at right angles with the refracted ray I *r*. That angle in every case is the *angle of polarisation*. With glass it is about 56° 35′, but must of course depend upon the refractive index of the glass.[1]

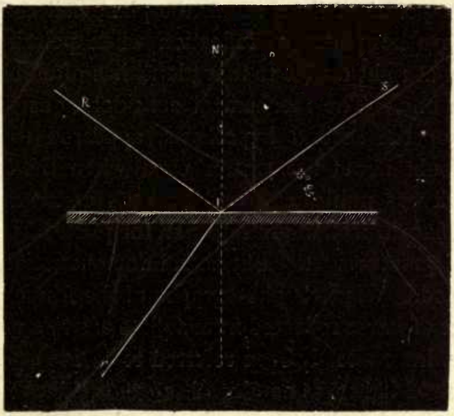

FIG. 148.—Angle of Polarisation.

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[1] Sir David Brewster long ago (*Phil. Tr.* 1815) advanced various arguments to show that the incident rays were probably subjected to the refractive influence of the reflecting body *before reflection*. This conclusion in itself, quite apart from Brewster's reasons, has received strong confirmation from phenomena since discovered. That plane-polarised rays are rotated when

It follows that, as the refractive index of glass or any other medium differs for different colours, polarisation by reflection can never be quite perfect for *all* the colours of white light at any one angle. The imperfection is, however, so small, that it may be neglected for all but very highly refractive substances, or very delicate experiments.

131. **Direction of the Vibrations.**—The question whether the actual vibrations which constitute the wave in a ray of plane-polarised light, are *in* the plane called the plane of polarisation (the plane of reflection when polarised by that method) or at right angles to that plane, has often been treated as an open one. The mechanical considerations above cited in favour of the second hypothesis, appeared to myself to leave no doubt about the matter even when the first edition of this work was published; and Stokes's experiment on the effects of a fine diffraction-grating upon the plane of polarisation[1] was also of great weight. But actual demonstration has since been afforded. Wiener's photographs of the fringes caused by interference of waves reflected from a plate of silver with the incident waves, have already been referred to (§ 119). Now when plane-polarised light was employed at an incidence of 45°, the interference bands were produced when the plane of polarisation was the same as the plane of incidence, but none when at right angles to it, showing that the actual vibrations were parallel to the reflecting surface. And finally, in Hertz's rays of electrical radiation (§ 120) we know the plane of electric

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reflected from the pole of a magnet in Kerr's experiment (§ 177) seems to show, as Dr. Lodge points out, that the wave is influenced by a layer of iron of a certain depth before reflection. And Drude (*Wied. Ann.* xliii. 158) has very lately ascertained that the thin black portion of a soap-film (see § 121) has a polarising angle differing from that of the much thicker coloured part of the film, the difference amounting to as much as seventeen minutes of arc. Lord Rayleigh has also proved that surface impurities affect the phenomena; which likewise implies that a certain thickness of film has an effect upon them.

[1] See *Cambridge Trans.* 1850.

oscillation; and using sheets of metal as reflectors, Trouton has shown that the rays are reflected at all incidences when the vibrations are parallel to the reflecting surface or perpendicular to the plane of polarisation, but at a certain angle are not reflected when the vibrations are in the plane of incidence.

132. **Polarisation by Double Refraction.**—Having determined the direction of the vibrations in a "plane of polarisation," we can now consider the phenomena of a doubly-refracting crystal. It has been assumed that double refraction is due to an *inequality of elasticity* in different directions within the crystal. Is there then this inequality? Experiment shows us not only that there is, but that the physical properties of a crystal in this respect stand in fixed and invariable relation to its optical properties as tested by experiment; and that both these again have a fixed relation to its form. Some crystals are symmetrical in all directions, as the cube; if heated, these conduct heat equally in all directions; and with variations in temperature they expand equally in each direction. Such crystals may be assumed to be equally elastic in all directions, and accordingly, in a free or natural condition they have *no double refraction.* But if now we take a crystal of quartz, which crystallises in six-sided prisms with pyramidal ends, it is manifest on inspection that it is not geometrically symmetrical in all directions, but only round one axis, that of the prism. Take a slice cut parallel to this axis, A (Fig. 149), and pierce it with a hole into which we can introduce a wire heated by an electric current or otherwise. Coat the plate with a film of wax, and introduce the heated wire: the wax will gradually melt around it, and it will soon be seen that the melted surface is an ellipse; in other words, the heat is conducted more rapidly along the

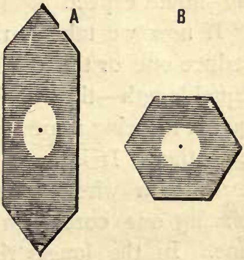

FIG. 149.—Quartz Plates.

crystallographic axis than across it. Doing the same with a slice cut *across* the axis, B, the melted area is now a circle; showing that conduction is equal in all radial directions round the axis.[1]

It has further been determined by experiment, especially by Professor Mitscherlich, that when a crystal of this description is heated or cooled, it expands or contracts unequally in different directions. Almost if not quite invariably, a moderate heat expands the shorter axis of the perfect crystal more than the others, or brings the crystal *nearer* to the form of a cube, or other shape, which in its most perfect and simple form can be inscribed in a sphere (this is the simplest general sign of the form of a non-doubly-refracting crystal). With this change comes a diminution of the inequality in elasticities, which, at a certain temperature, may even altogether disappear, as we shall hereafter demonstrate by a beautiful experiment, due also to Professor Mitscherlich (§ 193). The various faces of such crystals also show very different powers of cohesion; and even different resistances to the disintegrating action of chemical re-agents. Finally, it has been shown directly by Savart, who strewed fine dust upon plates of doubly-refracting crystals cut in various directions, and then excited sonorous vibrations in the plates, that there are such differences in actual elasticity as we should expect.

If now we take a rhomb of Iceland spar or calcite, and reduce one or the other of its faces till all the edges are of equal length—the true form of the crystal—we find it resembles quartz in being symmetrical around one axis A A (Fig. 150), and no other. It is as if we took the skeleton outline of a cube made with wires, jointed at each corner of the cube, and placing one corner on the table, pressed down the opposite one. In the longer rhomb, also depicted in Fig. 150, the direction A A *parallel* to the other is still the true crystallo-

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[1] This experiment is due to Senarmont.

graphic axis, round which the crystalline molecules are symmetrically built.[1] If we cut a plate with artificial faces perpendicular to this axis, and melt wax from a heated centre, as with the quartz, the melted area is circular.

Take now a ray passing along this axis. The vibrations, being perpendicular to the ray, are therefore perpendicular to the axis, and in all these perpendiculars the elasticities are equal. There ought, therefore, to be no double refraction. If the crystal is so cut that a ray can be thus transmitted, we find it is so; there *is* no double refraction; and the axis is therefore in this case the *optic axis* of the crystal.

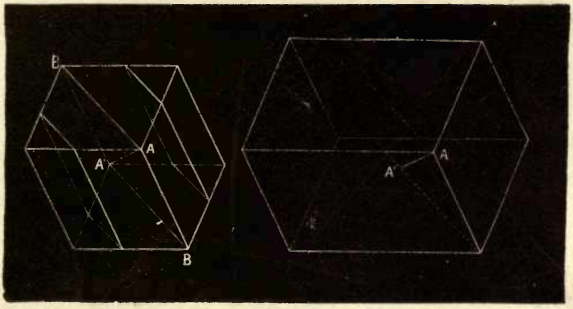

FIG. 150.—Axis of Iceland Spar.

But now let the ray pass through the crystal at a right angle with this axis. The elasticities being equal all round the axis, that in the direction of the axis itself must be either greatest or least—in the calcite it is greatest. The axis itself, in such a case, is a plane of vibration at right angles to the ray (and therefore such as luminous vibrations require) in which the ether vibrates most freely; and at right angles to this is another plane in which vibration is most retarded. According to the

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[1] The axis is a mere *direction*, which at any point in the crystal, if it were split so that there was produced an obtuse solid angle at that point, would be an axis to that angle.

simplest mechanical principles, all the azimuths of vibration in the ray must be resolved into these two, and the ray be thus divided into two, differently refracted, and oppositely polarised.

Take next an intermediate position; for instance, lay the rhomb on a flat table over a black spot; the ray sent perpendicularly in the direction A B (Fig. 151) to an eye over the spot, is neither parallel to, nor at a right angle to the axis. But its vibrations, being necessarily at right angles to itself, may be represented by lines drawn on a piece of card laid on the top horizontal face of the calcite. Draw two such lines at right angles to each other, to represent planes of polarised vibration, *a b*, *c d*. The card can easily be turned round so that there is a position in which *a b* is *perpendicular to the axis*, the direction of least elasticity; and the other line, *c d*, is that of the greatest elasticity possible in the front of a wave travelling in this direction, and must obviously lie in the same plane as the axis. Into these two directions, therefore, will such vibrations be resolved; and the two images will always be in the line *c d*, which is in the same plane as the optic axis.

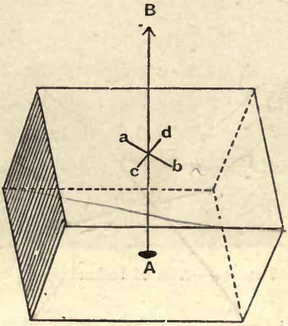

FIG. 151.—Direction of Vibrations in the Spar.

133. **Principal Planes or Sections.**—The plane thus passing through *c d* and the optic axis, and all planes or sections parallel to it, are called *principal planes* in the crystal. Thus

in Fig. 150, not only is the plane A B A B a principal plane, but the other parallel planes drawn are principal planes. As therefore one of the two planes of polarisation, in a ray incident in a principal plane, coincides with that plane, and the other is perpendicular to the axis, the elasticities on both sides of the plane of incidence are equal, and both refracted rays remain in that plane, though differently refracted. It will be soon found on trial that all planes perpendicular to a natural face of the spar, and including the optic axis, are principal planes.

But if the ray passing through the spar is oblique to both the optic axis and the faces of the crystal at which it enters and emerges, the case is different. Cut a small cross of card and stick it by a pin on the end of a thin rod, like a child's windmill, to represent—the rod the ray direction, and the arms of the cross two rectangular polarised planes. Take another rod and adjust it in a position to represent the optic axis. The latter being merely a direction, the *actual* axis any given ray is concerned with is that which intersects the ray; move the optic axis rod (parallel to itself) therefore, till it intersects the rod representing the ray. It will be now found that the cross can always be turned round so that one arm is at right angles to the axis: this therefore, being always the *least elasticity possible* in the calcite, represents one of the polarised planes of vibration, and being at right angles to the axis or plane of greatest elasticity, the forces on each side of that plane are equal, and this ray will follow the ordinary law of refraction. But the other plane of vibration is not now either in the plane or the axis of greatest elasticity, or at right angles with it; but oblique to it. The elasticities in which this plane of vibration is concerned are therefore unequal on different sides, and so this ray is deflected to one side or the other, the refracted ray not remaining in this case in the plane of incidence, but being bent aside.

134. **Indices of Refraction.**—Lastly, it can easily be seen that in calcite the index of refraction for the polarised ray whose vibrations are in every case at right angles to the axis,

must be constant, and be the highest; whereas the index of the "extraordinary" ray must vary, from that same index down to some lowest figure due to the greater ease of vibration in the direction of the axis itself.[1] In calcite the two indices are 1·654 for the ordinary ray, and 1·483 for the lowest value of the extraordinary ray. But in some other crystals (as in quartz, for instance) the elasticity may be *less* in the direction of the axis than in directions at right angles to it. In that case the general phenomena will be the same, but the ordinary ray will have the *lesser* constant index of refraction.

135. **Wave-Shells in Uni-axial Crystals.**—We have thus accounted for the phenomena in crystals which have one axis of no double refraction. In both the cases (of which calcite is called a negative crystal, because the extraordinary ray is less refracted than the other, or the axial elasticity is greatest; while the other class are termed positive crystals) the *ordinary* ray proceeding from any point in the crystal would reach the same distance in any direction in the same time. An infinite number of points in different directions, at which the wave will have arrived at the same moment from a common centre, is called a wave-surface or wave-shell; in this case the wave-surface may be represented by a spherical shell. But in the calcite the "extraordinary" wave-shell similarly formed at the same instant by the terminals of rays sent in all directions from the same point, will be a spheroid *flattened* in the direction of the optic axis; with its flattened surfaces coinciding in the centres with the opposite axial points of the sphere, and its extended surfaces outside the sphere. In a positive crystal, on the contrary, the "extraordinary" wave-shell will be a *prolate* spheroid, of which the ends are coincident with the two axial points in the sphere, while the rest of the surfaces are inside the sphere. The two may be repre-

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[1] It must never be forgotten that the direction of the *ray* is at right angles to both sets of *vibrations* we are considering. In calcite, therefore, the ray itself travels *slowest* along the axis.

sented in section as in Fig. 152, where the radii as they cut the two curves represent the respective velocities of the two rays;[1] and the optic axis is the perpendicular to the common tangent of the two curves.

As a rule, the spheroid coincides at two opposite points with the spherical wave-shell; or the two "indices" correspond in one direction of the ray. But in quartz and a few other crystals, as we shall hereafter find, there is a peculiar kind of double refraction in the direction of the optic axis itself, so that the spheroid does not reach to the spherical wave-shell, but is altogether contained within it. It this case also, however, the optic axis is a common perpendicular to *parallel* planes which are opposite tangent planes to the spherical and spheroidal wave-shells.

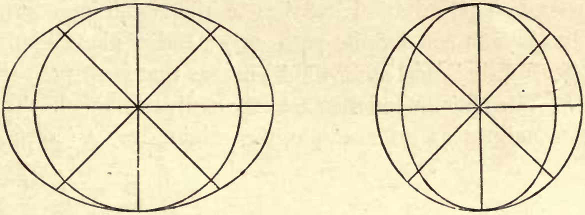
Negative. Positive.

FIG. 152.—Positive and Negative Crystals.

136. **Bi-axial Crystals.**—Sir David Brewster discovered that there were many other crystals in which neither ray obeyed the law of ordinary refraction; and further experiment showed that such crystals possessed *two* axes of no double refraction. The phenomena of these crystals are explained on similar

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[1] Of course the longer and shorter radii only represent the two velocities in the same precise direction. Any actual ray not passing along the axis itself must be divided into two separated by an angle, and these two separated radii will represent the velocities of the two halves of the ray. The precise geometrical construction for any given ray, as given by Huygens, will be found in any of the text-books.

principles, but must be studied more in detail later on. In them also the optic axes are the perpendiculars to planes, which are common tangent-planes to the two wave-shells.

137. **Phenomena of the Tourmalines.**—We can now readily understand the phenomena presented by our various apparatus. Considering the original beam of common light to consist either of vibrations in all azimuths, as at A, Fig. 144, or only of two at right angles with each other, as at B in the same figure,[1] which may, however, be at any angle with the horizon; in either case polarisation consists in the obtaining separately of vibrations in *one* definite path only; and "plane" polarisation (for we shall find other kinds) means that such path is in a plane. The phenomena then are very easily explained. Taking the tourmalines as an example, the original ray A (considered for convenience as compounded of two planes, or polarised rays, together) meets the first tourmaline, B (Fig. 153), so placed that the optic axis is vertical. We have already learnt that the ray must be divided into planes of vibration, one ver-

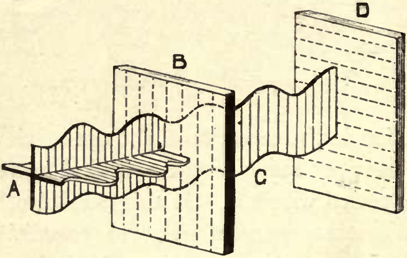

FIG. 153.—Action of Tourmalines.

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[1] Either hypothesis will account for most of the phenomena, and with the two double-image prisms in one position, we did certainly compound one beam (F, Fig. 139) out of two rectangular plane-polarised beams, which cannot be distinguished by any test yet known from common light. Nevertheless the theory that common light contains all azimuths is far the most probable, and best meets many important considerations. A brief summary of the matter is given in the Appendix to this chapter.

tical and the other horizontal; but the horizontal vibrations are all absorbed within the crystal, which from some arrangement of its molecules not understood, is (when of a certain thickness) absolutely opaque to them. Therefore only vertical vibrations can get through. The ray which emerges, C, is therefore plane-polarised, and if it meets a second tourmaline similarly placed, it will again get through. But supposing the second be placed as at D, all light must be stopped, as we have seen it is, though by two nearly transparent crystals!

The phenomena of the double-image prisms are explained in precisely the same way, except that in this case both rays get through the first crystal. When the second prism is at right angles with the first, the ray that got through the first would be quenched by the *same* plane of vibration in the second; but the plane at right angles with that allows it free passage. The phenomena of reflection and refraction do not need any further analysis; and it will only be necessary, before proceeding with our experiments, to describe briefly the most convenient polarising apparatus.

APPENDIX TO CHAPTER X.

The Vibrations of Common Light.

We have only been able to account for the phenomena of polarised light on the supposition that the particles of ether moved in perfectly definite orbits; and every experiment in this branch of physical optics, from first to last, confirms that hypothesis, which we shall see has also enabled most marvellous predictions to be made, afterwards verified by experiment. But when we proceed to ask, What are the nature and orbits of the vibrations in a ray of common or unpolarised light, we have propounded a question the answer to which is by no means easy. All that can be done here is to state briefly the chief results of the investigations various physicists have made into this interesting subject,[1] and finally to suggest what appears the most probable method of reconciling the chief difficulties.

If common light passes through a doubly-refracting film it is divided into two plane-polarised beams; and if these are not much separated, or supposing they are, if they are again united, the two together behave as common light (§ 137). This may be and has been accounted for on the theory that common light itself consists of two plane-polarised beams, the vibrations of which are in rectangular planes, so that a section of these planes across the ray would resemble A in Fig. 154. Such seems to have been the belief of Sir David Brewster, and partly of Fresnel.

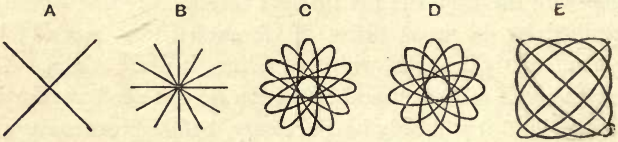

FIG. 154.—Theories concerning Common Light.

But this theory presents great mechanical difficulties. It is difficult to conceive that in any homogeneous transparent medium there should be any two given planes of vibration more than any others. Still more, either half of the ether particles vibrate in one plane, and half in the other, or else the same particle alternately vibrates in rectangular planes. The last supposition cannot possibly be entertained ; but even upon the other, *immediately contiguous* particles of ether must be vibrating in rectangular planes. This is difficult to explain on

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[1] It is right to state that great part of the following paragraphs are mainly a condensation, recast, of the summary of the subject given in the last edition of Müller-Pouillet's *Lehrbuch der Physik.* A translation, or version in any sense, is not pretended ; and the conclusion is not from that work.

any wave-theory, which supposes that each moving particle communicates *similar* motions to contiguous particles. And lastly, such a theory seems to suppose that there is really no unpolarised light at all, but only bundles made up of two oppositely polarised rays.

Fresnel therefore adopted the theory that the vibrations of the ether particles in common light took place in *all* azimuths, but that these azimuths were assumed *in succession.* On this hypothesis, taking for clearness only a few azimuths, a section of the ray may be supposed to be like B, Fig. 154. In adopting or describing this theory it is often added,[1] that with such inconceivably rapid vibrations as those of light, it is possible or probable that hundreds or even thousands of vibrations may take place in one plane, before they change into some other plane. But it is impossible, on reflection, to rest satisfied with such a supposition. If the vibrations thus remain constant in direction through any number, there is no reason why their direction should *then* change ; and in fact whenever we have, as in a polarised ray of any kind, one which we *know* vibrates many times in succession in one orbit, we also know that such orbit of vibration remains stable. The same is the case with the plane-polarised vibrations set up in Hertz's experiments ; the rays set up by such linear disturbances in free space, remain plane-polarised.

Other considerations also require us to carry our reasoning farther. If there be change, it must be either sudden (by steps, as it were) or by insensible degrees. Obvious mechanical reasons are against the first supposition ; and we are almost shut up, therefore, to the hypothesis of a gradual and continuous change in the path of vibration. But even if we suppose the elementary forms of such paths to be plane vibrations, such a gradual change must result in a curve ; and when we remember that an *elliptical* orbit is of all forms of polarisation the

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[1] See *Polarisation of Light*, by W. Spottiswoode, P.R.S. (*Nature Series*), p. 6. See also Deschanel's *Natural Philosophy*, last page.

most common in nature,[1] we are almost driven to take elliptical orbits into our purview. In fact Fresnel's own conception has been modified so as to consist of elliptical vibrations in various azimuths, resembling those of C, Fig. 154, rather than the plane orbits of B in the same figure. Such vibrations *gradually* changing azimuth would somewhat resemble the curve shown in D, Fig. 154. But the case is not only conceivable, but on every mechanical ground far the most probable, that any original elliptical vibration would not merely change gradually in azimuth, but also in *character*, gradually passing not only into circles, but also into straight lines. Such a curve is roughly indicated in E, Fig. 154, except that in the case of light we must conceive the changes infinitely more gradual, and so arranged that each recurring form (*e.g.* each recurring straight line) should be in a somewhat different azimuth. In this way we can not only easily imagine, but with any compound pendulum apparatus readily trace, a curve which shall give in succession every form represented by Fig. 155, which it will be seen at a glance presents every known variety of polarised light.

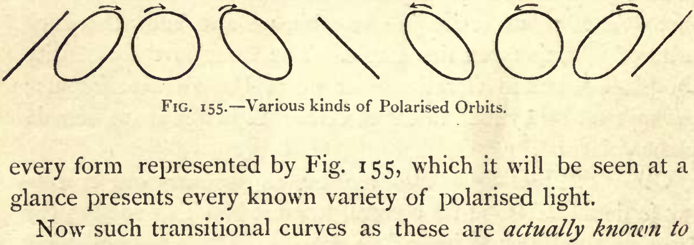

FIG. 155.—Various kinds of Polarised Orbits.

Now such transitional curves as these are *actually known to us*, being common to countless forms of acoustic apparatus. Two almost exactly unisonal tuning-forks with mirrors will produce them in the manner of M. Lissajous;[2] and they also occur in the *kaleidophone*, in the latter case being produced by the end of a single rod in a state of *transverse vibration*.

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[1] Elliptical and circular polarisation are explained in a subsequent chapter.

[2] See pp. 35, 36.

Many ingenious experiments appear to favour this hypothesis. Common light may by proper means be divided into pairs of oppositely-polarised rays of either of the three forms—plane, elliptical, or circular. Dove received a pencil of common light on a concave glass cone, whose sides met the rays at the polarising angle. There thus met at the centre, rays plane-polarised in every azimuth : the result gave no trace of polarisation. He then passed common light through a swiftly rotating calc-spar prism, thus producing a pencil polarised in a swiftly-rotated plane. Tested by a second prism, this rotated pencil showed no polarisation : tested, on the contrary, by the electric spark, it did; thus appearing to show that what we may call Dove's "artificial" unpolarised pencil differs from a natural one, chiefly in the greater *slowness* of the changes in its vibrations. Dove further caused a quarter-wave plate to rotate with the calcite polariser, thus producing circular and elliptic polarisation in all azimuths ; the sensible result was still unpolarised light. Finally the quarter-wave plate was fixed while the polariser revolved, thus producing in succession plane-polarised light in two opposite planes, and also elliptically and circularly-polarised light of opposite kinds. The result was still, sensibly, unpolarised light; but if the rotation was arranged so that the velocity in each revolution acquired two *maxima* and two *minima*, the sensible result appeared partially polarised. It is also well known that if a beam of plane or other polarised light be dispersed, or broken up by passage through many substances, such as a film of stearine,[1] it loses every trace of its previous polarisation.

All these considerations point to the theory which derives common light from vibration in some transitional figure of the nature shown in E, Fig. 154. But Lippich in 1863 started the objection that such curves, in acoustics, arose from combining oscillations of very slightly *different periods.* Now in light-

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[1] Sir David Brewster gives a list of such depolarising substances in the *Philosophical Transactions.*

vibrations, such different periods would represent *different colours;* and accordingly he suggested that according to this theory no *absolutely* homogeneous or one-coloured rays of common light could exist. Lippich himself adopted the hypothesis that it was so, and that all unpolarised light must and did necessitate periods sufficiently different, however infinitesimally so, to produce the compounded curves. This hypothesis is possible, and there appears no probability of any experimental means being devised sufficiently delicate to determine the point absolutely.

Nevertheless it does not seem to be by any means necessary. It does not appear to me to have ever been really demonstrated that transitional curves necessarily involve as their ultimate cause two different periods of rectilinear vibration, in the particular case where the vibrating body is under the physical conditions represented by a point in a stretched cord. On the contrary, cords prepared with the most scrupulous care to avoid any sensible inequalities of tension or elasticity on any side, give phenomena of the same character; and countless experiments tend strongly to show that the character of the orbit described by such points, depends rather on the particular *application of forces* to the point in the cord. It is quite possible to produce vibrations in a cord which remain nearly in one plane for a considerable period, and, by a different application of force, to produce most complicated curves. By threading silvered beads upon the strings, it has been shown that different performers cause the same string of the same violin to vibrate in different curves. We even know that, supposing a stretched cord or the end of a rod to be deflected radially by a given force, if a moment later any other force be applied tangentially to the former the result *must* be a curve of some kind. The character of these curves is also affected by surrounding conditions; for it has been found by experiment that the string of an old and fine-toned violin has a very sensible tendency to vibrate in more simple or "closed" curves, than that of a rougher, inferior instrument; thereby accounting for the purer tone.

Now there are some reasons to believe that the constitution of the ether may be such, that at any given point of displacement the forces acting upon it do somewhat resemble those acting upon a stretched cord. Moreover such vibrations afford the easiest and best conception of the possibility of the infinite number of periods and wave-lengths in a ray of white light. A stretched cord not only vibrates as a whole, but in all the segments or harmonics of which it is capable: and though these are limited in number in our limited cords, if we conceive a cord of infinite elasticity, and of such infinite length as compared with any wave-length of light as we must conceive in the case of waves in the ether, we at once account for waves of all periods being simultaneously propagated along the same cord, as the hypothesis requires. Further, even with a mechanical cord of the greatest possible length, wave propagation (such as the transmission of a "shiver" caused by striking near one end) is one of the swiftest we know which is capable of being traced by mechanical means. With molecular motions of sufficient rapidity to cause luminous rays, any given particle of ether may be, before it has ceased to vibrate under the influence of any given motion, influenced by another motion in quite a different direction. These motions may be complicated, especially, by displacements of the ether *in the direction of the ray itself.* These may act upon the transverse vibrations, though not luminous themselves, just as transverse vibrations in a cord are caused by a pull at the end.[1] There appears no difficulty, therefore, in conceiving that transverse vibrations may be perfectly synchronous, or produce absolutely homogeneous light, and yet assume transitional forms.

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[1] Professor Stokes has shown that although longitudinal displacements of the ether particles cannot give rise to luminous phenomena themselves, it is to some extent necessary to take them into consideration in regard to certain results.

In any case it appears far the most probable that the vibrations of common light, whether thus accounted for, or upon Lippich's hypothesis, do take place in such transitional orbits as are represented (in skeleton only) by E, Fig. 154, and that the forces acting upon the displaced ether-particles in a ray of light resemble those acting upon a stretched cord, unhampered however by its limited ends and other mechanical imperfections. The capabilities of this supposition long ago struck Sir John Herschel; and it appears to me to cover more ground and to present fewer difficulties than any other. I have sometimes thought that it lends itself better than most other hypotheses to Clerk-Maxwell's, or, in fact, any other conceivable electro-magnetic theory of light. And it is very remarkable, to say the least, that if by means of smooth glass guides we compel any part of a cord to vibrate in a rectilinear or other fixed orbit, all other harmonic vibrations take place in a similar orbit; offering thus a striking analogy to the effects of polarising a ray of light.

CHAPTER XI

POLARISING APPARATUS

The Nicol Prism—Foucault's Prism—Improved Prisms—Large and Small Analysers—Care of Prisms—Nicol Prism Polariscope—Glass Piles—The ordinary "Elbow" Polariscope—Direct Reflecting Polariscopes—Rotating the Reflected Beam—Simple Apparatus for Private Study—Nörrenberg's Doubler.

138. **The Nicol Prism.**—The tourmaline is an admirably simple polariser or analyser; and it gives a "field" of any angle, which makes it very convenient for "eye" work: it is however too small for large polarisers, and its colour is a serious drawback.[1] The polarisation by Iceland spar is also perfect; and as this spar is as clear as glass, if we can abolish one of the rays we shall get a colourless and perfectly polarised beam. This was effected by Nicol in the prism which bears his name. Reflecting that the two indices of refraction varied considerably (they are 1·48 and 1·65), and that Canada balsam, so much used for cementing lenses, was intermediate between these, he cut a crystal of spar about thrice as long as its diameter,

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[1] The largest tourmaline known belonged to the late Dr. Spottiswoode, and was over two inches square. Strange to say, its colour and polarising properties were both remarkably good. It is difficult now to get really good plates, tolerably free from colour, more than $\frac{3}{4}$ inch square, and such a plate is worth several guineas.

through A B, Fig. 156, and cemented the sections by a layer of balsam. Then a ray C D on entering the spar is doubly refracted, one half more so than the other. The *most* refracted half finds in the layer of balsam a less refracting medium; and obviously, if the angle is oblique enough for the respective indices, must be "totally reflected" to one side, and is thus got rid of. The other ray finds in the balsam a denser medium, and therefore passes through.

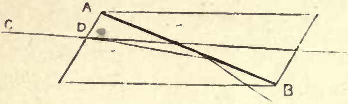

FIG. 156.—Nicol Prism.

139. **The Foucault Prism.**—Foucault carried the idea of Nicol farther; and by employing a film of *air* instead of Canada balsam between the two halves of the prism, made about one-third of the spar suffice which Nicol's construction requires. Fig 157 shows the Foucault prism. The ray, A B, is doubly refracted as before, and one of the rays totally reflected; but air having so much lower a refracting index, the "cut" may be much less oblique to the ray. The aim is, as in Nicol's construction, to let one ray pass, while the more refracted one meets the air at an angle of total reflection. Owing to the less obliquity, however, there is less "angular field" in this prism; that is, a beam must be nearer parallelism for all the marginal rays to get through—practically the convergence or divergence must not exceed about 8°. Also, the

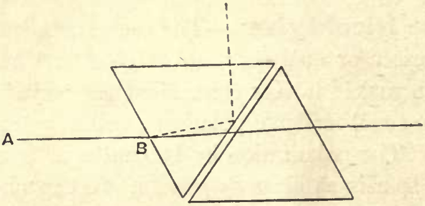

FIG. 157.—Foucault's Prism.

two surfaces of the film of air cause a perceptible loss of light by two partial reflections, even in the ray which does get through. This is not very great, however; and a large Foucault prism is only about one-fourth the cost of a Nicol of the same aperture.[1] I have never tested the matter, but am inclined to think the loss of light as compared with a Nicol would be about 10 per cent.

140. **Improved Prisms.**—Nicol's form of prism is often made with the ends cut rectangularly to the axis. Such need a longer piece of spar for the same area and give less angular field, but the reflection from the inclined faces is avoided. Hartnack and Prazmowski made a great improvement by cutting the spar into an artificial shape, so that the cemented section was at right angles to the optic axis. So cut, the angle between the two rays was greater, and it was further utilized to the utmost by making the joint with linseed oil, which is much nearer the lower index of refraction—hence the prism was shorter and had more angular field. Messrs. Steeg and Reuter further improved this prism by making the section from edge to edge, instead of from corner to corner of a parallelopiped, thus doubling the area of a pencil for a prism of the same length.

These prisms need double the spar which a Nicol consumes, and the extra cutting makes them about three times the price; they are therefore chiefly used in small sizes, for analysing purposes or for the microscope. Some of their advantages can be obtained by a plan devised by Professor S. P. Thompson. Taking a crystal rather longer than necessary for a Nicol, the ends are cut off so as to make the

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[1] Besides requiring only a third of the spar, and much spar being available which is useless for a large Nicol, there is no troublesome balsam-joint to make, the cut faces only needing to be polished. Mr. C. D. Ahrens, who has made all the gigantic Nicols for Dr. Spottiswoode and others, has informed me that the joint of such a Nicol may require thirty hours of unremitting attention over a fire, as it is impossible to leave the task when once commenced, till the balsam is baked thoroughly hard.

slant the reverse way, as in Fig. 157A, the new end faces being A B, C D. For a Nicol prism the section would have been made along A D, but the shortened piece is cut along B C, the section being thus nearly at right angles to the optic axis shown by the arrow. The prism stands thus midway between a Nicol and Prazmowski, but is very easily made.

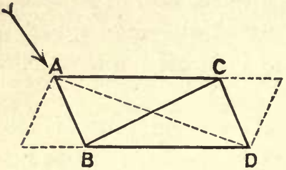

FIG. 157A.

Glazebrook and Thompson have also made square-ended prisms with the optic axis at right angles with the length, which is the best construction of all. Mr. Ahrens has constructed this form in three pieces, as in Fig. 158, the optic axis lying across the diagonal of the end face, as shown by the arrow. This cuts the spar with little waste, and the spar is only one-half the length for the same area; but the edge of the centre wedge, in every specimen I have tried, produces a faint duplicate image, and consequently this form fails as an analyser. For microscopic use, when spar is procurable, it is the best polariser I know. The same ingenious cutter has also constructed large polarisers (of two inches square or more in area) made up of a mosaic of small prisms, which have been used instead of single Nicol prisms in such instruments as presently described; the sections, when carefully made, not being focused, do not perceptibly injure the field on the screen in any way.

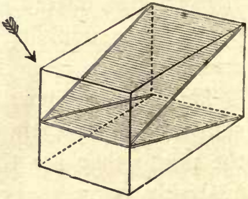

FIG. 158.—Ahrens' Prism.

The Foucault prism has been improved in a similar way to the Nicol, by cutting artificially with rectangular ends, and is then known as the Glan prism. Double-image prisms are also cut in various ways, and known by the names of Rochon and others.

All sorts of "artificial" Nicols have been made. The second half of a Nicol having no doubly refracting effect, glass might be substituted if a low enough density could be obtained, were it not for the "irrationality of the spectra." (§ 60). Jamin and Soleil employed an oblong cell with glass ends, filled with carbon bisulphide brought to the proper index with benzol. In this a mere film of calcite was adjusted so as to slant across in the proper position, then the action of a Nicol is precisely reversed, the total reflection taking place at the calcite, with the ray of *lower* index. The danger of this fluid might be avoided by the use of others less volatile, as mentioned on p. 17, but the inconvenience of a fluid is very great in apparatus constantly rotated. The same principle has been applied by Bertrand, using dense glass for the body of the prism, and a film of some crystal whose *higher* index corresponds, and which therefore totally reflects the ray of lowest index; but crystals suitable can only be obtained of small size.

The "Nicol prism," or one of its modifications, is the most perfect piece of apparatus we possess, owing to the *absolute* polarisation of all colours alike, and its freedom from colour. One about 2 inches long costs from 40*s.* to 60*s.*, according to circumstances, and should be fitted in a tube which fits and rotates on the nozzle of the objective (N, Fig. 1) to serve as an analyser. A large Nicol also makes the most perfect "polariser"; and the cost, which is many pounds (when procurable at all), is its only objection. If such a prism can be afforded and obtained, it should be mounted in front of the lantern flange, so that the full parallel beam passes through it, and so as to be capable of rotation. With such a polariser, we can turn the lantern direct to the screen, which is a great advantage; as also is the power of rotating the full beam as to its plane of polarisation. But, on the other hand, a large Nicol for *analyser*, as formerly used by our chief lecturers, I consider a mistake in almost every way.[1] We must manifestly focus on the screen all the slides we employ, by a lens which will converge and cross all the rays. Now referring to Fig. 159, it will be seen that unless the lens be of long focus, the small Nicol, properly adjusted at the crossing point, allows every ray to pass through it which can possibly get through the larger one, however large it be; and thus a small Nicol so adjusted actually saves absorption of light through a great length of spar. Moreover, we can adjust a small Nicol in this way precisely, and focus with precision by the rack and pinion of our objective; whereas with a monster Nicol in front, both the object and the focusing lens have, as usually mounted, to be coarsely adjusted by hand, and much light is scattered about the room. Again, to ensure getting most of the rays through a long Nicol, a lens of long focus has to be employed; which either necessitates a long screen distance,

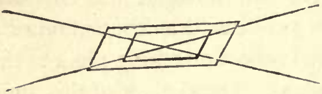

FIG. 159.—Large and Small Analysers.

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[1] A little qualification is necessary, because in some investigations it is desirable to carry a beam of *parallel* light through polariser, object, and analyser, to a prism or other apparatus; and for such experiments a large analyser has obvious advantages. Such experiments are however few, belong chiefly to scientific investigation, and are not suitable for projection. It is scarcely necessary to state that nothing is further from the purpose of these pages than any depreciation of apparatus which is the admiration—almost the envy—of other than the happy possessors. The first pair of large Nicols made for Dr. Spottiswoode were of distinct scientific value, as being the precursors of this kind of apparatus, never before made on such a scale (they were about 2½ inches clear aperture, and larger ones were afterwards made for the same gentleman, over 3¼ inches). And the larger a polarising Nicol can be secured or afforded, the better. But I certainly do desire to make clear to science-teachers and others, that very nearly all the experiments capable of projection by these magnificent instruments can be equalled on the screen at a far less cost, and that, as Dr. S. P. Thompson has also lately expressed it, it is "almost a sin" to waste a large Nicol in this way.

or gives a smaller image, and will hardly show any rings in crystals without additional and special apparatus. For these reasons, and after seeing experiments performed with large Nicols repeatedly, I adhere to an opinion based upon experience, that such a lantern-front as described in Fig. 1, with a small analyser adjusted at the right point, gives more light, a better disc, greater facility in manipulation, and *superior effects* in almost every way.

141. **Care of Prisms.**—Calcite is very soft, and all prisms made from it, of any kind, need special care. Nicols are often mounted with glass caps, which protect them while enabling them to be used; but if light is rather deficient these may have to be removed; caps should also be taken off for a few minutes before experiment, to allow the dew to evaporate which at first condenses when the light is turned on. If any dust or dulness has to be removed, the surface should be cleansed *solely* with a camel-hair brush of the finest quality. Small ones are best cleaned with a swan quill cut rather short; large ones require a round-nosed "sky-brush" of double that diameter. The application of ordinary chamois leather, as to lenses, would soon cover the spar with scratches. Another rather important point with *large* Nicols, is always to put them away with the balsam-joint standing perpendicularly. If one half rests upon the other, the weight of the top half may gradually produce "thin film" colours in the layer of balsam. Mr. Ahrens tells me several fine Nicols have suffered for want of this precaution, and have had to be taken apart and rejoined.

142. **Nicol Prism Polariscope.**—I now describe a projecting polariscope (which is of course capable of private or eye-work also, by the light of a candle or that from a window) made for myself on this principle; and especially as I have never even yet seen an instrument which, taken all round, was capable of such a variety of work with so little trouble and such rapid facility in manipulation, especially in the dark; a column of fluid, or the convergent arrangement for wide-angled

crystals (see § 190) being added or withdrawn in twenty seconds. The adjustments have all been most carefully planned, several details of value being suggested from their own experience by Messrs. Darker, who constructed the original apparatus with much care and skill from a Nicol of barely two inches diameter, but of great purity, made for me by Mr. Ahrens. As the result of experience, some points have since been constructed of modified form for me by Messrs. Newton and Co. The drawing is on a scale of three inches to the foot.

B (Figs. 160 and 161) is a base-board, barely twenty-four inches long, and six inches wide, in which mahogany slides, H (Fig. 160), are secured by screws, L (Fig. 161), which tighten the dovetailed or rebated slides. The screws bear upon slips of brass fixed to the slide-bases, H, as usual. On these bases are screwed brass standards which carry separately the polarising Nicol, P N, the stage and focal power, S, F, and convergent lens system when required (Fig. 161).

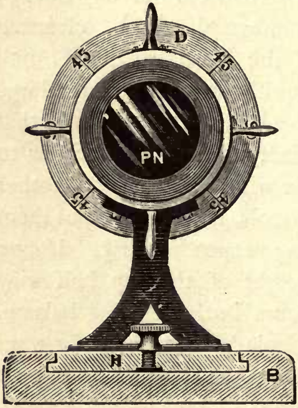

FIG. 160.

The large Nicol, P N, is mounted in an inner tube, fitted in a larger tube—partly for appearance and partly to accommodate a rather larger Nicol should such ever be acquired. To save useless weight and space, its corners are cut off in a hexagonal form. The outer tube carries at the end next the lantern a flange, D (Figs. 160 and 161), divided into forty-five degrees, and at its middle four spokes, by which it can be rotated in collars screwed to the standards. Two of these spokes are

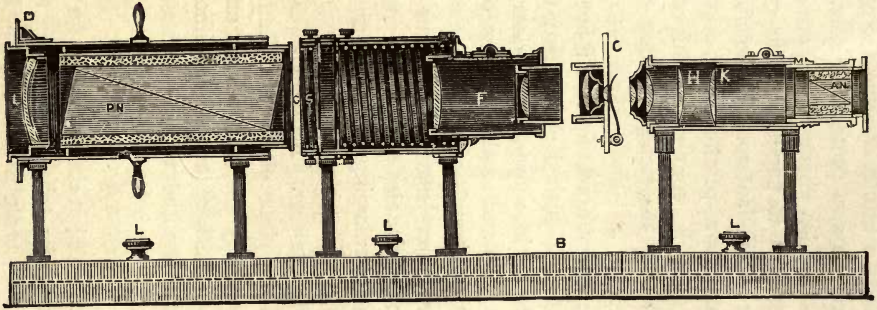

FIG. 161.—Projecting Polariscope with Nicol Prism Polariser.

B is the baseboard, with slides at the sides, in which all the pieces can slide easily, but with fair accuracy.

L L L are screws to fix the pieces when placed in their proper positions.

P N is the polarising Nicol, mounted in cork in a brass tube. This is adjusted in an outer tube truly in the optic axis. The outer tube is turned by four handles round the centre, arranged at the polarising axes, and with differently-shaped heads (as round and square) so that the position of the polarised plane may be known in the dark.

D is a divided circle or flange. The Nicol is protected by a glass plate G at the front end; at the other end may be either another plate, or a slightly concave lens L, to parallelise slightly convergent rays from the condensers.

S is a spring slide-stage.

F is the focusing power with rack and pinion. S and F together are practically the optical front of Fig. 1, adapted to this instrument. The nozzle of F fits all the apparatus.

A N is the analyser, here shown as a square-ended linseed-oil prism by Steeg and Reuter. In ordinary polarising experiments this analyser fits into the nozzle of F.

C is a system of three convergent lenses, with a circular stage and springs for crystals, whose brushes are to be shown in highly convergent light. It fits into, and is revolvable in the nozzle of F, or is instantly removable. When in use a second very similar system is brought near the crystal, nearly bringing the rays to parallelism. This is finally done by the field lens H, and the brushes are finally focused on the screen by the lens K, the rays from which cross in the analyser. By varying the distance of H from the convergent system, and having two different lenses K, a wide variety of foci and sizes of disc for these brushes can be readily obtained.

bright, and two blackened, the latter also having a groove turned round them; so that the polarised planes can be known in an instant either by sight or in the dark. In the same end of the outer tube screws a fitting carrying the concave meniscus lens, L, or a plane glass to protect the spar, at pleasure. The object of the lens is, whenever the utmost illumination is required, to reconvert to parallelism the converging rays from the condenser of the lantern. Thus a four-inch beam can be brought down to a parallel beam of two inches; but usually a plane glass is employed, and G is another plane glass cap slipped over the smaller tube at the other end of the Nicol.

The slide-stage and power are shown drawn forward; but in ordinary use the end, S (Fig. 161), is pushed up, so that the end of the Nicol, G, projects into S, close up to the slide-stage, and no light can escape. The stage and focal power are precisely the same as in Fig. 1; but two lengthening adapters, and an extra lens of six inches focus, either lengthen the focus an inch, or by using the back lens only, give also foci of five inches and six inches. Another method of enlarging the image, sometimes convenient in special circumstances, is to adjust a concave "amplifying" lens in front of the analyzer. A tube for fluids, eight inches in length, closed by glass plates with leather washers and screw fittings, is borne by forked standards on a mahogany base which drops into the base board, but without dovetails, and can be inserted at G or withdrawn in an instant; or a flat-sided bottle or cell of fluid can be inserted with the same facility.

The analysing prism, A N, is mounted in cork, which is fitted into an *inner* tube sliding in an outer tube. The latter, for ordinary work, fits into the nozzle, F, as already described. By the inner sliding tube the analyser can be adjusted so as to come as nearly as possible at the actual crossing-point of the rays for various kinds of work. Much pains should be taken in selecting this analyser, many Nicols being cut so as to waste a great deal of angular field. Various prisms will differ by a large percentage, and one should be chosen which will let through (without showing the white limit to the field) as large an angular pencil as possible,—or, in other words, which has the widest (efficient) aperture for a given length. One and a half inches to two inches in length of side is the best average size. The best analyser is a Prazmowski prism, which, with a focal power of about $3\frac{1}{2}$ inches, just "clears," or shows without cut-off on the side, a circular slide of $1\frac{5}{8}$ inches diameter.

In Fig. 161, the apparatus is shown with a convergent system of lenses for exhibiting the rings in wide-angled bi-axial crystals (see Chapter XIV.). The first system of lenses, C, fits into the nozzle of F, and is provided with a circular stage barely three inches diameter, furnished with two ordinary micro-stage springs. This stage will carry any crystal, mounted anyhow, whether in wooden slides as hereafter described, on ordinary micro-glasses, or in the well-known square German cork mounts. The second system slides tightly into the end of a tube carried by a separate standard and mahogany base; and into the short tube bearing it can be fitted at pleasure, a cork ring carrying a selenite quarter-wave plate (see Chapter XIII.). The coloured figures are not true images, but merely interference fringes appearing at the back of the three re-converging lenses; and as they there appear, have to be magnified and focused on the screen. This is best done by so adjusting a rather large field lens, H, an inch or so behind the combination, as to collect and decidedly converge the rays, while another convex focusing lens, K, with the analyser, slides in a racked tube beyond. One or two lenses which fit at K will give a great range of distance and image. The analyser itself should also be capable of sliding in its mount, so as to be adjustable at the best crossing-point of the focused rays. I now prefer to have it mounted with different sizes of collar at the two ends, one fitting into F, and the other sliding down the tube, towards the lens K, by which the analyser is easily adjusted for both positions alike.

Besides these attachments, I formerly often used another tube, the small end of which fitted into the nozzle of F, and carried a spring and slide-stage or slot, brought as near F as possible. Into the other end was fitted a sliding tube carrying a low micro-power and the analyser. This formed an oxy-hydrogen microscopic power of $1\frac{1}{2}$ inches focus. The whole light of the polariscope is condensed by the front lens of F upon the small slide stage, protected as usual by alum-cells, either in the slide-stage S, the ordinary slide-stage of the lantern, or both, as required: and the polariscope thus arranged will project a large number of micro-slides—not all, but a large class which would not be shown at all by the ordinary power. Such a simple attachment enormously increases the range of the instrument, bringing hundreds of cheap and easily accessible slides within its scope, particularly sections of rock. A section of porcupine quill, for instance, one-fifth of an inch in diameter, can be then projected at twelve feet distance, about 30 inches diameter. For higher powers there is not sufficient light, and the projection-microscope with polarising apparatus must be employed.[1]

The whole of these arrangements, with Nicol, double-image, and thin glass analysers, fluid tube, Huygens's apparatus, and two ordinary crystal stages, with a small box for rotators and any special slides, packs in a case 30 × 10 × 7 inches; and the base-board will carry the whole apparatus described in Chapter XIV., for projecting wide-angled bi-axials through a tube of rotatory fluid eight inches long (§ 206).

143. **Polarising Glass Piles.**—The next best polariser to calcite is a bundle of glass plates. A brass or tin elbow may be made, as Fig. 162, one end, N, fitting on the flange-

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[1] This instrument is fully described in *Optical Projection*. It will project the coarser of the starches with the lime-light alone, and with the electric arc, of course, much more.

nozzle of the lantern, the other end as short as possible, ending in a screw-collar, B, exactly the same size and thread as B in Fig. 1, so that the objective and optical stage will screw into it. At the corner of the elbow is fitted the pile of oval glass plates, G, made of the thinnest and most colourless glass procurable. Ten or twelve are sufficient, but the back one must be blacked on the back, and the whole so arranged that the light from the condensers impinges upon and leaves the glass at an angle of 56° from the normal. Such an elbow and bundle, with the objective screwed in, and a Nicol fitted on the nozzle, is the ordinary "elbow" lantern polariscope. It gives a large field of polarised light, and for nearly all purposes the reflector is almost as good as a large Nicol; but it has the two disadvantages, that the lantern has to be turned off sideways, on account of the elbow angle, and that the original plane of polarisation cannot be rotated, which is desirable for some experiments.

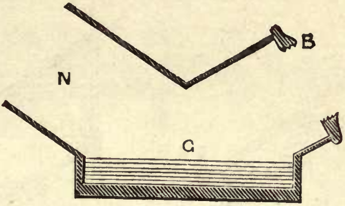

FIG. 162.—Elbow of Polariscope.

To meet this objection, some have employed a glass pile working by the transmitted light, which can be mounted and rotated just like a Nicol. This meets the objection just stated, but has another—viz., that it is difficult to get *complete* polarisation in this way. If such a refracting bundle is employed, not less than eighteen plates should be used, and the angle should be somewhat *greater* than the polarising angle, by which nearly all unpolarised light may be reflected and so got rid of.

The greatest fault of such a pile so used, however, is that it usually gives a perceptible green colour, owing to the thickness of glass. The "ten or twelve plates" often mentioned, do not polarise the whole beam by a great deal.

144. **Direct Reflecting Polariscopes.**—Of late there has been an absolute famine of Iceland spar, and this has turned attention to the improvement of reflecting projection polariscopes by the abolition of the angular deflection, as suggested long ago by Delezenne. His idea was to bring the rays back into a direction parallel to their original incidence, by an additional reflection; and this is done by modern opticians in two ways.

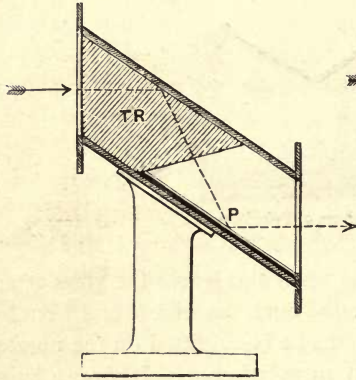

FIG. 163..

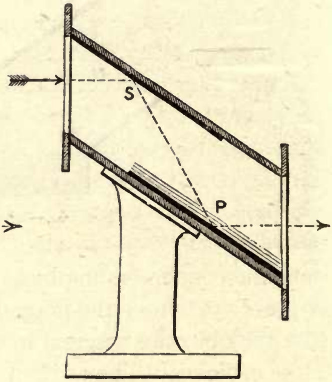

FIG. 164.

Mr. Ahrens constructs a Delezenne polariser as in Fig 163. Here the parallel beam from the lantern is first deflected by a massive totally-reflecting prism of glass, T R, whose end faces are normal to the incident and emergent rays; then the rays fall at the proper angle upon the polariser, P, either a plate of black glass, or two or three thin plates with a blackened one at the bottom. This construction is however costly, so massive a glass prism being expensive; while the absorption of light is also serious.

The Rev. P. R. Sleeman prefers the construction in Fig 164, which is much cheaper, more easily adjusted, and on the whole better in my opinion. Here the silvered glass mirror, S, replaces the reflecting prism, and P is a "pile" with a blackened glass at the bottom. This can be made in a very cheap form, and of any size desired. In the first instruments made upon this plan the optical beam, which is necessarily deflected several inches from the axis of the flange-nozzle, though restored to parallelism with it, was brought down below that axis as by Fig 164. This made the apparatus high and awkward-looking, however; to obviate which a side deviation was next tried. That also, however, did not look well, and necessitated a large case. To obviate these objections I reversed the polariser so as to deflect the beam upwards, and Messrs. Newton and Co, the principal makers of this class of apparatus, now construct the instrument on that model, as shown in Fig 165. It will be seen that it is thus made as compact as the Nicol construction. All except the polariser is precisely the same as shown in section in Fig. 161.

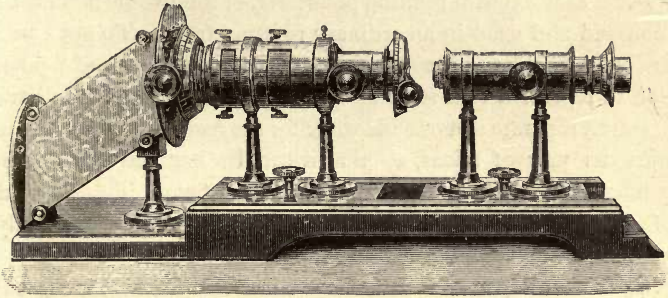

FIG. 165.—Direct Reflecting Polariscope.

Like the "elbow" form of polariscope, the Delezenne polariser cannot of itself rotate the polarised beam; but this operation, so desirable for many experiments in rotary polarisation, is easily effected in a manner suggested by Professor S. P.

Thompson. It will be seen later on that if the plane-polarised beam is passed through a mica quarter-wave film properly adjusted, it becomes circularly polarised; and if in front of this film we place another which can be rotated, the beam becomes again plane-polarised, in a plane depending upon the position of the second film. Such an arrangement of two films can either be mounted permanently next the polariser, with the second plate in a divided circle and actuated by spokes, as usual with rotating polarisers, or the two micas can be mounted and used in an ordinary rotating frame. To get a perfectly dark field, the second mica must be in the "crossed" position to represent that state of affairs. It is convenient to have at least a separate slot or slide-stage for the reception of the frame with its pair of micas, so that it can be handled quite independently of anything in the ordinary slide-stage. This method of rotating the polarised beam can of course be equally applied to the common "elbow" polariscope.

145. **Analysers.**—Besides the Nicol or Prazmowski prism, it is well to have a glass analyser (Fig. 166) formed of eighteen or twenty pieces of microscopic cover-glass, G, placed at the proper angle in a tube which fits at N on the nozzle of the objective. An aperture, R, in the side of the tube, allows the reflected ray also to be used. For reasons already given, such an arrangement is not equal to a Nicol; but it gives a large field, is very instructive and interesting in throwing complementary images of *all* phenomena on screen and ceiling, and will do *thoroughly satisfactory work* for all to whom 40*s.* or 60*s.* for a Nicol prism may be an object. In fact, a

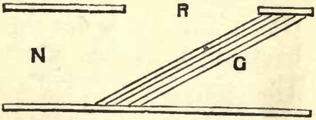

FIG. 166.—Thin Glass Analyser.

glass reflector and thin glass analyser are within the reach of any one who can work in brass.[1] A tourmaline is also useful; and either a double-image prism, or a pair of these mounted in a Huygens's apparatus, will of course be provided.

146. **Table Apparatus.**—For merely private study very cheap and simple apparatus will suffice. Make a shallow paste-board or wooden tray, A (Fig. 167), 1 inch deep, say 7 inches by 4 inches. Drop into it thin glass plates to within $\frac{1}{4}$ inch of the top, cleaning them well, and blacking the back of the bottom one. Cut two wooden or pasteboard side pieces, E, united across the top by another piece, D, and fill in the ends by a piece of *ground*-glass, B, 4 in. square, and another, C, of *clear* glass the same size. The light will fall on the ground glass as shown by the arrow, if it is turned towards a lamp or the window; will be nicely softened and scattered, and polarised by the pile in the bottom; and the objects can be laid on the clear glass at C to be examined by the small pile of microscopic glass, P, contained in a round or square card-board tube. The "elbow" polariscope already described also makes a capital "table" polariscope, if a disc of fine ground-glass, to soften the light, be fitted into the end, N (Fig. 162), which goes on the flange of the lantern. It will be found that the lenses pleasantly focus the objects in the slide-stage, which are examined by looking in through the analyser on the nozzle.

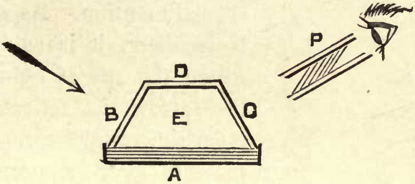

FIG. 167.—Simple Table Polariscope.

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[1] My own *first* glass analyser was fitted up by myself, and used, in a pasteboard tube.

In fact, a small Nicol, or tourmaline, or pile of thin microglass fixed slantwise in a tube, as analyser, and the light reflected from any glass plate, or the top of a mahogany table, as polariser, will suffice for many experiments.

147. **Nörrenberg's "Doubler."**—There is a form of polarising apparatus to which I have ventured to give this name, and which is so useful if the student does any personal work with thin films, as to need special mention. As designed by Nörrenberg, it is as in Fig. 168, where the ray of light shown by the arrow is reflected at the polarising angle from the *single* plate of glass, F, normally to the horizontal piece of looking-glass, H. It is thence reflected perpendicularly upwards, passing this time *through* the polarising plate to be examined by the Nicol, or other analyser, at N. It will be obvious that if the object be laid on the stage at E, the phenomena are as usual. But if it be placed between the polariser and the looking-glass, at D, the polarised ray has to pass *twice* through the film or object to be examined, which is equivalent to doubling the film in thickness. The use of this "doubling" in ascertaining the thickness of thin films, will appear in the next chapter; and there are other peculiar uses of this form of apparatus. A very simple construction will answer all real purposes, however. Knock out the opposite sides F and B of an oblong box—such as a cigar-box—and on the remaining sides fix guides for the polarising plate, P, at the proper angle. On

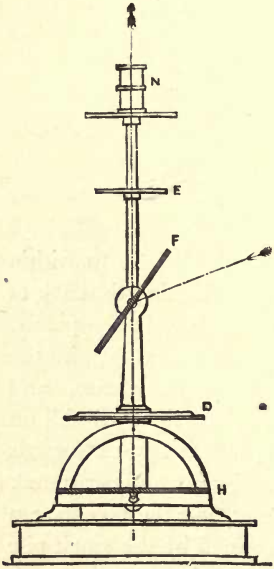

FIG. 168.—Nörrenberg's Doubler.

one end, R, lay a piece of good looking-glass the size of the end ; and in the other end cut a hole in which the Nicol, N, or other analyser, can be rotated (Fig. 169). The object can be held between P and R, or in the case of gauging films, laid on the looking-glass itself. For most purposes of the "doubler" no focusing lenses will be required. I have even laid a piece of looking-glass on the table, and arranged over it a plate of clear glass at the proper angle by means of the Bunsen universal holder (Fig. 17), holding the Nicol in my hand. But for ascertaining the polarising planes in films the box form is best. It should then be made with great accuracy : and the glass mirror R should be cut truly square, and be scratched with a diamond on the face along both diagonal and rectangular diameters, all passing through the centre of the plate. The use of these lines will be seen in the next chapter.

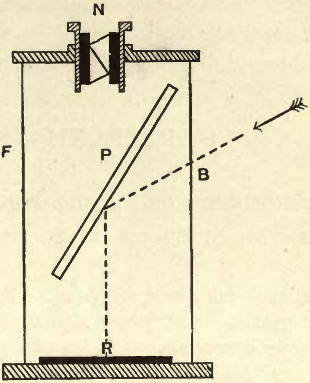

FIG. 169.—Simple Doubler.

CHAPTER XII

CHROMATIC PHENOMENA OF PLANE-POLARISED LIGHT.—LIGHT AS AN ANALYSER OF MOLECULAR CONDITION

Resolution of Vibrations—Interference Colours—Why Opposite Positions of the Analyser give Complementary Colours—Coloured Designs in Mica and Selenite—Demonstrations of Interference—Crystallizations—Mineral Sections—Organic Films—Effects of Strain or Tension Stress in Liquids—Effects of Heat—and of Sonorous Vibration—Appendix: Mica Film Work.

148. **Resolution of Vibrations.**—We could have formed no conclusion as to the precise orbits of the molecules of ether in our polarised waves, apart from the phenomena; but if we have rightly interpreted these, then any one acquainted with elementary mechanics and the "resolution of forces" will see that we can test such a theory by experiment. Dealing with motions whose direction we are supposed to know, if we are correct we can "resolve" those motions. Taking a vertical plane of vibration, for instance, and supposing ether-atoms moving freely in the plane orbit A B, B A (Fig. 170), if we interpose in the path of a wave consisting of such motions, a plate of crystal whose structure is of some such sort as shown in the figure, as only permits of vibrations being executed in the planes C D, E F, the motions in the vertical orbit A B must be resolved into the other two planes, which make angles of 45° with the original plane.

This strictly mechanical resolution of a plane of motion into two, when the wave-motion encounters a substance presenting rectangular planes of greatest and least resistance at any angles with the orbit of motion other than 0° and 90°, will be readily understood from a strictly mechanical analogy. Let the substance be a piece of very straight-grained board; and the motion be that of a narrow saw-blade cutting through it. While the saw cuts either exactly "with the grain," or at right angles across it, there is no tendency towards deflection of the cut. But if an attempt be made to cut across the grain at an angle of 45°, a strong tendency will be felt towards deflection on one side or the other, and a straight cut will be found almost impossible. It is to meet this difficulty that cross-cut saws intended for miscellaneous straight work are made with a narrow "set" and thin blades. The saw-blade cannot divide itself into *two* cuts; but the free ether-atoms are able to do so, and hence

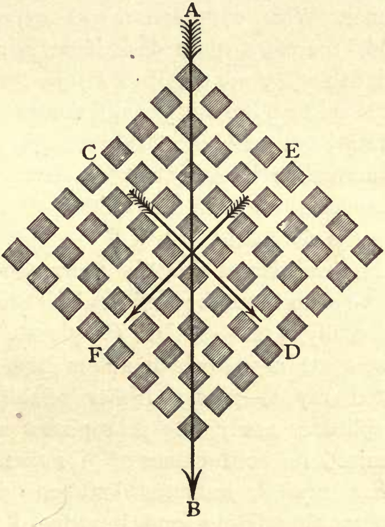

FIG. 170.—Effect of a Crystalline Film.

are "resolved" into *both* set of rectangular motions, into which the saw-cut tends to deviate.

It would seem already that we have obtained this resolution of motions, from the duplication of our images when the two double-image prisms were placed at an angle of 45° with one another, and from the transmission of about half the light through two tourmalines superposed at the same angle. If we are right, the two oblique planes must both be also capable of resolution in their turn, by the analyser, into perpendicular and horizontal planes. When our polariser and analyser are crossed, and the "field," therefore, quite dark, if we interpose between them a tourmaline at 45° we ought to *restore* the light. Cross therefore the Nicol or other analyser till the screen is dark, and insert the rotating tourmaline. Truly enough, as we rotate it, though the tourmaline is really a brown tint, mounted on a clear glass, it appears, when in the position of B, Fig. 141, as a *light* image on the dark field.

We, have, however, learnt that the tourmaline stops one of the rays, and we wish to see beyond doubt if the original plane of polarisation really is resolved into *two* planes. We therefore want a slice of some crystal which allows both halves of the doubly-refracted ray to pass. Either selenite[1] or mica is convenient, splitting easily into thin plates, which transmit the rays polarised in both planes of vibration. Let a thin plate of either crystal, mounted between glass discs, be placed in the rotating frame, and introduced into the stage when the analysing Nicol is crossed. On rotation, we find two positions in which no effect at all is produced; but in *two* positions[2] midway (or at 45° angle) between these, light is

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[1] Selenite is the crystalline form of gypsum or sulphate of lime.

[2] The two positions might in a sense be termed four, because the analyser, or a crystal in the stage, when rotated 180° is turned upside down. This however brings the polarising planes or axes into the *same* directions again, when all the phenomena repeat themselves; hence in polarising experiments positions *diametrically* opposite, or 180° apart, are considered and spoken of as identical.

restored. With the tourmaline, the restored light would be extinguished by turning the analyser across the position of the tourmaline, the other tourmaline ray being absorbed; but with the selenite or mica this cannot be done, showing that the original plane-polarised beam has been resolved into two; either of which can be extinguished by the analyser, but not both together.

149. **Interference Colours of Plane-Polarised Light.**—But if in this experiment the plate of crystal is very thin (such as opticians always supply for experiments) we encounter a fresh and very beautiful phenomenon. The light restored by the thin plate or film is *coloured* light. This phenomenon becomes still more beautiful if we use a double-image prism as analyser, and an aperture in the stage along with the film, giving two discs; then we get two coloured images of the aperture, and if the discs are large enough to overlap, where they do so the light is white, showing that the two are *complementary* colours. The most beautiful demonstration of all is with the Huygens apparatus, which was mounted so as to introduce a crystal-film between the two prisms; then each of the two pencils doubly-refracted and polarised by the first prism is resolved by the selenite, and again by the second prism; and we have therefore *four* beautifully-coloured images revolving round each other as the analyser is rotated. With the prisms alone, we could compound *one* beam when the prisms were crossed; but with the selenite inserted we can never get less than three, as we readily see on analysis ought to be the case.

We can understand this colour. In every bifurcation of the ray, this is doubly-refracted because of the unequal elasticity already referred to (§ 132). Hence we not only have the two rays, but one ray is *more retarded* than the other. We can "see" this in a large piece of Iceland spar, for one of the images of a black spot seen through it appears nearer than the other; and it is the same even in the plate of selenite, though the two rays are not in such a thin film visibly separated. The two rays, so long as they vibrate in planes at right angles to each other in and after passing through the selenite film, cannot of course interfere. But the analyser resolves and doubly refracts each of them a second time, and brings portions from each *together again into the same plane.* Now in the rigid plane orbit of our original polarised beam, we have that *identity of origin* which we have already learnt (§ 101) is necessary for two beams to interfere; and in the identical plane into which portions of the two beams separated by the selenite are again united by the analyser, we have that *closeness of path*, or nearly so, we also found to be necessary. We bring together again, then, into the same plane (that of the analyser) two rays of originally identical origin, one of which, during separation, has got behind the other in passing through the film, by a given distance depending upon the thickness of the film of crystal. But whilst in reflection from a "thin film," one ray is retarded by *twice* the thickness of the film; in this case one ray is retarded by the *difference* in velocity, whilst both traverse the same film. Of course a much thicker film is required to produce the same retardation in this latter case; and of course also, the greater the difference in the two indices of refraction, the thinner the film must be to produce a given colour. Too great a thickness, of course, gives no colour, for the very same reasons too thick a "thin film" gives none (§ 107).

We soon find, and it readily appears, that if we turn the analyser round 45° when the film is in the stage, the colour also disappears. Interference no longer takes place, because one of the rays from the film now passes the analyser unchecked and unmodified, while the other is stopped. Similarly, when the polarising planes of the film coincide with and cross those of the polariser and analyser, there is also no colour—indeed no effect at all; the rays from the polariser passing through the parallel one of the two planes in the film without modification.

150. **Cause of Complementary Colours.**—To understand the "complementary" colours, we must take into ac-

count the *direction of the motion* as well as the plane of vibration of the ether-atoms, at each moment of bifurcation or resolution into two planes, and of re-combination by the analyser. Let us suppose the original ray A, Fig. 171, plane-polarised in a vertical plane, is at the phase when the atoms are moving *downwards* when it encounters the selenite with its planes at 45°. The bifurcated rays must obviously have their motions in the directions B and C. Now B, when again resolved by the analyser, must take the directions D and E, and C of F and G. A double-image prism would transmit both, but by our Nicol analyser, either crossed or parallel, one plane or other is stopped. It will be seen on inspection of Fig. 171 that when the Nicol is in the position which allows the two *perpendicular* vibrations to get through, these two (D F) are in the *same phase* of their orbits, and so coincide with or strengthen each other; but if in the position in which the horizontal vibrations get through, E and G are in *contrary phases*, or destroy each other. However, therefore, the two sets of waves come together in one position of the analyser, as regards any wave-length, that particular wave-length must meet in exactly *opposite* phases, in the other position at right angles to it. If the two waves are exactly destroyed in one position of the analyser, they are fully combined in the other; if half destroyed in one, they are half reinforced in the other, and so on.[1] Taking therefore the

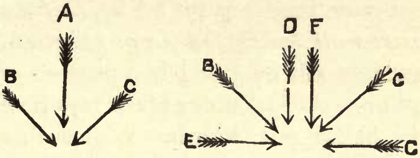

FIG. 171.—Resolution of Vibrations.

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[1] It will be seen in a subsequent chapter that the rectangular vibrations emerging from the film are chiefly compounded into circular and elliptical orbits. These are, however, again resolved by the analyser into rect-

whole range of wave-lengths throughout the spectrum, and considering the series of interferences, in every one of which the vibrations constituting light are divided into sets differing by half a phase or wave-length, it is evident that whatever is lacking from the spectrum in one position of the analyser, must be present in the opposite position, and that a beam of white light must be divided into two complementary colours. These colours may vary indefinitely according to the thickness of the film, but will always be of a composite, and not a pure spectral character. This will be demonstrated presently by spectrum analysis ; but meantime, to put it briefly, *half a wave difference in phase reverses all the phenomena in polarised light.* A very simple illustration will be found in a plate of crystal "half a wave thick," or so thick that one of the rays is retarded behind the other by half a wave-length. With such a plate in the stage, the crossed analyser gives a bright field, and the parallel analyser a dark field; and if the plate is used with a coloured film or design, the colours are changed by it to their complementaries.

It is further evident, that in addition to any retardation or difference of phase due to the difference of velocity in the two rays while passing through the doubly-refracting film, when the polariser and analyser are *crossed* there is an additional difference of phase of *half a wave length*, since E and G (Fig. 171), *irrespective of any thickness of the film*, are in opposite phases. We shall see that this fact is of great assistance in accurately measuring the thickness of films.

151. **Coloured Designs.**—A film of selenite, or mica, varying in thickness, will of course give varying colours, so far as the thicknesses lie between the limits of colour. A thin slice split irregularly from selenite soon shows that this is so ; and if we have designs ground away of studied various thick-

angular planes ; and the student will easiest grasp the subject at this stage, by confining his attention to the simpler representation of it here given. For the effects of Composition, see §§ 160–164.

nesses, we may form stars, butterflies, flowers, birds, &c., of their appropriate colours, which they owe to nothing but the interferences of polarised light! Such designs are prepared in selenite at all prices from 3*s.* 6*d.* to £3 3*s.*, and there is a strange fascination about them, changing as they do to complementary colours at every quarter-revolution of the analyser, and giving, as already explained, no colour at all when that is at an angle of 45°. A plate ground conclave gives of course "Newton's rings," and a plate ground slightly wedge-shaped, similarly gives straight parallel coloured bands. Such wedges may be ground with water on very fine ground glass, and afterwards mounted in balsam between two glasses. Small reductions of thickness may be ground in selenite with the rounded end of a slate pencil and some putty-powder, and polished with more putty-powder on a piece of wash-leather.[1] The effect just now explained of a half-wave plate, in causing opposite or complementary effects, is often illustrated in selenite work by two designs in which the essential parts are a half-wave in thickness. One is the bust of a lady, which in one position of the analyser appears white, while in the other she becomes a dark mulatto or negress: the other is a representation of a miller's man with a bag of flour on his shoulder, who by the same revolution of the analyser becomes a sweep with a bag of soot.

152. **Mica Designs.**—But the best crystalline film for students is *mica*, the same that is used for gas-light covers. Choose for polarising preparations a slab as clear and even as possible, free from minute air-bubbles or opaque deposits.[2]

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[1] The finest selenite preparation I have ever seen was executed entirely with his own hands by Mr. C. J. Fox, F.R.M.S. The subject was one of the grotesque-looking tropical fishes, and it had occupied him at intervals for many weeks. Every detail was worked out with minute care, and by the aid of rotational colours as explained further on, the eye appeared to wink as the analyser was rotated.

[2] Mica from different parts of the world differs very greatly in character. Generally it is a bi-axial crystal; but the angles vary, and one kind known

This splits easily into thin laminæ, and is easily cut through by a penknife to greater or less depth. This rough and simple process will enable any student to prepare illustrations of the elementary phenomena so far described. A piece of mica thin enough to begin to show colour, is readily trimmed round with a strong pair of scissors to a disc the proper size for the wooden frame of a polariscope slide. Then the outline of such a simple design as Fig. 172, or the still simpler outline of a cube, can be cut to a small depth with the penknife, when a needle-point will lift and split off a thin film—it will be seen at once that the whole figure is now a different colour from the ground. Cutting further, through the outlines of the points, each is easily made a different thickness, displaying each point in a different colour. Laying the preparation on the table polariser shown in Fig. 167, the position in which most colour is shown by a crossed analyser is easily found with sufficient accuracy, and the mica mounted in that position in the frame. Another pattern easily made in this way is one of concentric squares, lifting first a thin film from a large square, then cutting and lifting with the needle another square $\frac{1}{16}$ of an inch smaller inside of it, and so on.

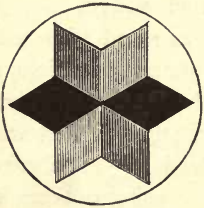

FIG. 172.—Mica Design.

as Canadian phlogophite, is uni-axial, and shows a strong diffractive six-rayed asterism, owing to small particles or crystals. Generally the best for preparations is Indian, and is slightly brown; but some specimens have a green and others a yellow shade: clearness and *minimum* colour for a given thickness, are the main points. Occasionally I have found small specimens clear white, but never so large and perfect as to be useful: large pieces of such (heretofore only found in Labrador, I believe) would be very valuable. A great deal of mica has iron deposits between the laminæ—such is worthless. The true crystalline form is an elongated hexagon, and I possess a piece showing this perfectly sharp at every angle: iron deposits also sometimes show these lines very accurately and curiously in the films.

Mica can also be *scraped* away carefully with a penknife to shaded or gradually lessened thicknesses, and fair representations of fruit or large flowers scraped out in this way, working of course on the table polariscope, with the mica in position and viewed through the analyser. The mica will appear clouded or semi-opaque where scraped; but when mounted in balsam and benzol as presently described, this disappears, and all becomes transparent again.

But mica is so easily capable of far more accurate, instructive, and scientific results than these,[1] and practical acquaintance with these results is so unequalled for its power of giving an intuitive understanding and realistic conception of the phenomena of polarised light, and their nature, that I would strongly urge every serious student who has leisure, to *make for himself* a full set of illustrations.[2] The necessary details respecting these will be given as they occur in order; and in the Appendix to this chapter will be found practical directions as to the general manipulation which I have found most suitable and easy for producing high-class work of this class.

The most valuable of all mica-film preparations is the wedge, designed by Mr. C. J. Fox, F.R.M.S., shown in Plate IV. at A. This consists of twenty-four $\frac{1}{8}$ wave-films superposed, each one $\frac{1}{16}$ inch shorter than the one beneath it—then if the thicknesses are accurate, the whole will give the first three

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[1] See for the first description of many of these preparations my paper on "Optical Combinations of Crystalline Films," *Proc. Physical Soc. of London*, 1883, and *Phil. Mag.*, May, 1883.

[2] It may encourage him to do so, to state that every slide or preparation described hereafter, into which mica enters, has been executed from first to last by my own hands. It was Mr. C. J. Fox, F.R.M.S., who first allowed me to see what could be done in this way, and told me something of his methods; and I commenced by merely imitating the beautiful preparations designed and executed by him. As I was soon able to add largely to these, so doubtless some reader may add yet further to such demonstrations of phenomena not only most instructive, but above all others magnificent in spectacular display. Prof. S. P. Thompson has already added to the repertory his rotation-index shown in Fig. 191.

orders of Newton's interference colours, each order divided exactly into stages successively increased by $\frac{1}{8}$ of a wave of retardation. A in Plate IV. shows the effect in the polariscope, with the analyser crossed. Of course the retardation can only be exact for one particular wave-length, which is always chosen for yellow light, as both medium in length and most brilliant. Then with analyser crossed, yellow light is extinguished; but a little blue (being shorter) and a little red (being longer) is not perfectly destroyed, and these residuals produce a little light of reddish plum-colour, the "tint of passage" as it is called, between the first and second orders. The second and third tints of passage are more positively red. But the *precise* thickness needed depends a little on the light to be chiefly used. For daylight work, very slightly thinner $\frac{1}{8}$ wave-films will be needed than for gas-light, which is deficient in blue rays and rich in red. Arc light is a little more blue than daylight; the lime-light comes between that and gas. Too thick films will make the twenty-fourth band perceptibly bluish, but may be correct for gas-light; and *vice versâ*. Therefore if such a wedge be ordered of a physical instrument maker, any light to be habitually used should be stated with the order.

153. **Demonstrations of Interference.**—That the colours of crystalline films really are produced by the greater retardation of one ray, and subsequent interference, may be proved by several independent methods. First, we can easily stop one half of the bifurcated ray. Place in the stage any slide—say a concave Newton's ring slide. The rings being at their brightest, and with the analyser exactly crossed, introduce, in front of the selenite, the rotating tourmaline at an angle of 45°. This stops by absorption *one* of the two rays into which the original polarised beam is divided; there are no longer two rays to be brought into interference, and accordingly, over the area covered by the tourmaline, the colours disappear.

Secondly, we may retard the other ray, and thus bring the two again into coincidence. If one ray be retarded in the selenite or mica more than that vibrating at right angles to it it is plain that, taking two films of equal thickness, if both are superposed the same way of the crystal, the colour must be that of a plate equal to the sum of both; but that if one be turned round 90°, the retardation of one ray by the first will be neutralised by the second, and no colour at all produced. If we place two similar films in the stage, in the two different separate positions, we find that it is so; and similarly, if the films be of different thickness, the colour will be in one position that of their sum, and in the other of their difference. A striking demonstration is furnished by rotating a selenite wedge over a similar one. The colours differ remarkably according to their positions; black (when the analyser is crossed) being necessarily produced wherever exactly the same thicknesses come into rectangular positions, and so causing in one position a black diagonal line. Therefore if a concave plate be rotated over a convex plate, the phenomena of the rings vary in a beautiful manner, black rings appearing in certain positions; or an even film of the proper thickness, rotated over the concave, will give the same beautiful phenomena. Again, if a film of even colour is rotated over a star made of separate points in different positions, the colours of the points are affected very differently, and in what appears (seeing the rotated film is the same thickness all over) a most wonderful manner till we understand the reason.

The most instructive and pretty demonstration of these reversed or counteracted retardations is, however, furnished by two precisely similar "step" wedges built up on Mr. Fox's plan.[1] The glass discs will nicely take a wedge $1\frac{1}{4}$ inches long

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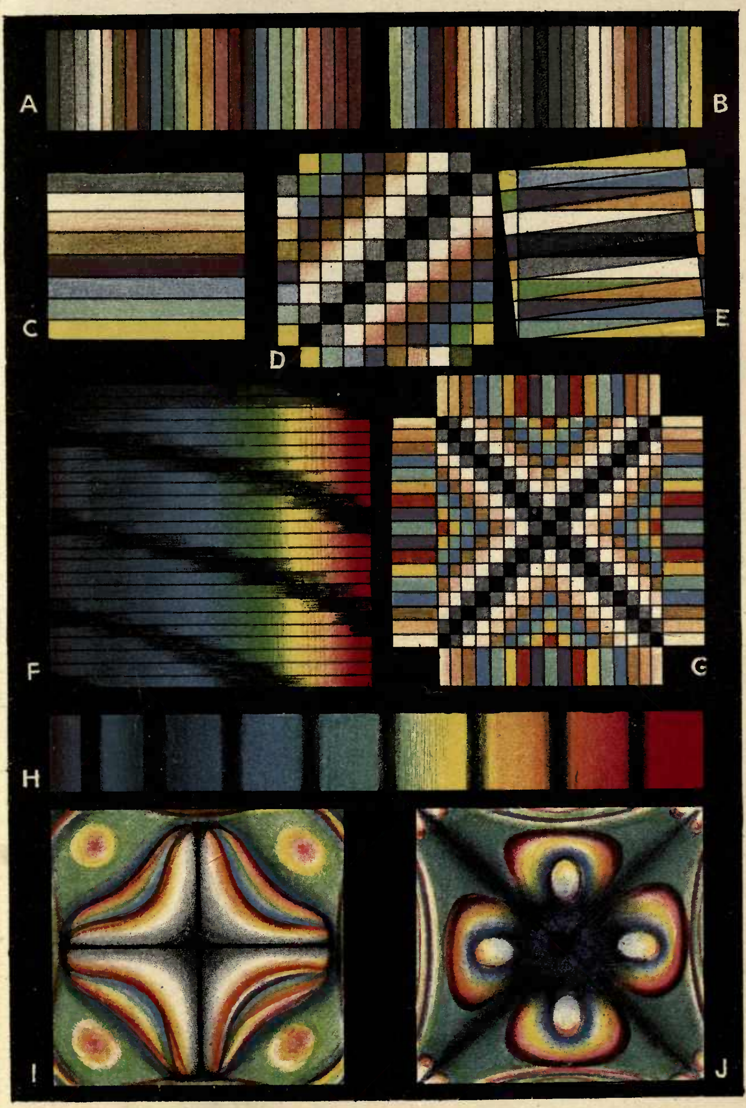
[1] The first few $\frac{1}{8}$ wave thicknesses giving poor colours—only pale fawn and blue-greys—the broadest or foundation film of the wedge is best about $\frac{5}{8}$ wave thick, as mentioned for designs. I think about $\frac{1}{6}$ wave thick for the others gives the most pleasing gradations, but it is only matter of preference.

by 1 inch wide, and this breadth is conveniently divided into eight steps $\frac{1}{8}$ inch wide. It is sufficient if each *corresponding* step in the two wedges is cut from the same film. One wedge being mounted in wood, and the other used in the rotating frame, when one is superposed on the other with the polarising planes in same positions and the thickest part of one over the thinnest in the other, we have an even colour. When the two thickest sides are superposed, if the polarising planes are parallel the tints grade with double the amount of difference in colour; if the planes are crossed there is no colour at all. When the wedges themselves are crossed, in one position there must be a central diagonal row of black squares, the other squares giving a beautiful chequer pattern of various colours. And when the rotating wedge is diagonal, there will be a pretty pattern of backgammon points. Two wedges built up of similar even films thus offer one of the most fascinating and instructive polariscope combinations. (See C, D, E, Plate IV.) Or should the student have sufficient skill and patience to build up a wedge of 24 $\frac{1}{8}$-wave films, if a single film be superposed on it with its principal plane crossed, and of a thickness equal to the twelfth stripe, or $1\frac{1}{2}$ waves, it is plain that middle stripe must appear black; and as on each side of it each equidistant stripe must present an equal *difference* or essential thickness, the coloured stripes will be symmetrically arranged on each side of the black one. (Plate IV. B.)

This is easily extended to still more beautiful designs in crossed films. At G on Plate IV. is shown a pair of crossed double-wedges; that is, each successive narrower film is laid down on the middle of the one underneath it. The phenomena of D. are now presented in each corner of the combined pattern, the black stripes crossing in the centre; or if one wedge is inverted on the other so as to bring the planes into the same direction, we get the same beautiful floor-cloth pattern in the addition colours, instead of the crossed colours. Either a concave selenite showing Newton's rings, or a mica prepara-

Pl. 4.

INTERFERENCES OF POLARIZED LIGHT



A. *Wedge of 24 ⅛ films*

B. *Ditto with 1½ mica crossed*

C. *Wedge of 8 films*

D.E. *Two C Wedges crossed*

F. *Spectrum of A*

G. *Two "double" wedges crossed*

H. *Spectrum of thick film of selenite or mica*

I. *Square of chilled glass*

J. *Same with polarizer and analyser at 45°*

tion, built up of concentric circles, as in Fig. 173, may also be crossed upon such a "circular wedge," as is illustrated further on in Fig. 185, using for mica circles the same thickness as for the other slide. The result of either will be most beautiful black radial spirals starting from the centre.

Lastly, we can prove the cutting out of certain colours by interference, by our never-failing method of spectrum analysis. Place a slit in the stage with a film which shows colours, and focussing it on the screen, pass the light from the analysing Nicol through the bisulphide prism. There will be crossing the spectrum one or more dark interference bands—more with a thicker film : in fact as the film increases, more and more bands appear in various parts of the spectrum, just as in the light reflected from a film of mica (§ 107), and showing, in the same way, how with a certain thickness we fail to get colour. This is well shown by subjecting a wedge to spectrum analysis, a slit being placed in the stage, and the wedge, with its bands parallel to it, gradually advanced over it from the thin edge to the thick one. It will be seen that, as the thickness increases, a greater number of the interference bands cross the spectrum, as we should expect, accounting for the paler colours. The spectrum of a plate of selenite too thick to show any colour at all, is shown at Plate IV. H. It is also seen, as we expect, that in contrary positions of the analyser, the bands occur in complementary colours. The two complementary sets of bands are easily shown together by using a double-image prism as analyser, arranging the two images of the slit in one line. The slits will then overlap in the space between the double image, giving there a white slit and complete spectrum ; while the two complementary spectra will appear at the top and bottom. If the slit be adjusted so as to cross the centre of a concave film giving Newton's rings, and

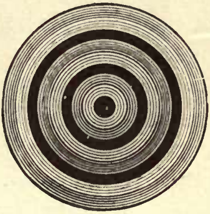


FIG. 173.

the slice of light be analysed by the prism, we get agai exactly the same interference bands as shown in Plate III. F

The best demonstration, however, is with our ever-useful Fo wedge. Turning round the stage so that it stands verticall with the stripes horizontal, we place with it a slit of black car or thin metal long enough to cross all the stripes. Th successive shifting of the interference bands, step by step, i now readily seen, as at F, Plate IV., the bands taking a obviously parabolic shape. The wedge alone only gives th interferences of Newton's first three orders; but by superposin with planes the same way, one or more mica or selenite film making up one, two, or more waves in thickness, the mor numerous interferences are readily demonstrated up to an other desired order.

154. **Crystallisations.**—Another beautiful series of ob jects showing gorgeous colours in the same way are *crystallisa tions*, from films of various solutions poured over glass discs, an then crystallised by evaporation. The only difficulty is t obtain the right thickness, as both too thick or too thin giv little or no colour, though light and shade effects can always b had as the analyser is rotated. For this reason, what ar called "superposition films" are very useful. These are thi plates of mica or selenite which give uniform colour (such ar easily split from mica) mounted between two glasses. On which gives blue and yellow, and another red and green, shoul be provided; then a film of crystals, or anything else whic shows no colour by itself, will give great variety when super posed on the film. There is a sameness about the colour produced by this plan, however, inferior to a slide which ca show its own colours.

A good arrangement for making crystallisations by evapora tion is shown in Fig. 174. On a wire tripod is placed one o the glass candle-chimneys so common, 3 inches diameter, an on the top of this is laid a square metal plate, not quite cover ing the chimney, having in the centre an aperture nearly a large as the glass disc, with three little projections bent up $\frac{1}{16}$ inch from the inner edge to keep the glasses in place. A spirit-lamp underneath gives a steady heat, adjustable by raising or lowering it. A saturated solution is not always best; often one mixed with equal bulk of water does better, and sometimes a little alcohol added helps effect. Great interest will be found in preparing slides with weaker or stronger solutions, and less or more heat, which will often entirely alter the character of the crystallisation. Thus, a solution of tartaric acid evaporated in the cold often crystallises in long straight lines, and in the sun in "stars;" whereas, when evaporated over the lamp, it gives irregular facets, very beautiful on the screen, and larger as the heat is greater. Salts which give a pattern too small in this way, may often be made to give much larger crystals by dissolving gelatine or gum in the saturated solution, and evaporating in the cold. The following are good polarising salts:—Tartaric acid, and most tartrates; citric acid, and most citrates; oxalic acid, and most oxalates; borax; chlorates; many nitrates; picric acid; sulphates of copper and magnesia, and the two mixed; most of the alkaloids and their salts; sugar—but in fact the list is interminable. Cubic crystals, being of equal symmetry and elasticity in all directions, do not polarise, unless in drying the film of crystals becomes subjected to tension, as it sometimes does (§§ 132, 157).

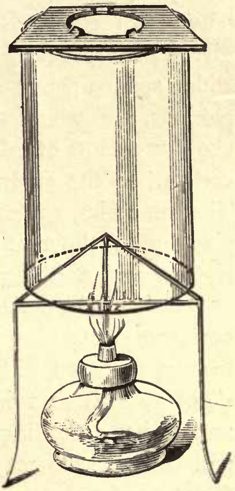


FIG. 174.—Apparatus for Crystallisation.

One of the prettiest crystals is salicine, which gives an enormous variety of effect, according to how it is treated. Some salicines I have prepared have been particularly admired for their gorgeous colours and size of the crystals. Such are attained by dissolving the substance in one part alcohol to four parts water, made rather hot, and saturated. Pour a *good* layer of this fluid on the glass, and evaporate quickly with rather a strong heat; the salt then *melts* in its own water of crystallisation, and beautiful crystals soon begin to form The heat then needs humouring in a way only experience can give, else crystals already formed may be re-melted and the slide spoiled; but when all goes well the result is simply glorious, the whole slide being covered with circular crystal showing sectors of colour like miniature "Newton's discs," and each, when the analyser is crossed, exhibiting a black cross The same film, cooled and breathed on whilst the crystals form gives quite different phenomena, in the shape of circula ripples, and a thinner film different again. Almost every operator has some little secret of his own; and one of my correspondents sent me a slide of the small sort of singula beauty, prepared with gelatine. The effects range from disc $\frac{1}{16}$ of an inch to 1 inch in diameter, of *any* colour, or black and white, according to the thickness. Citrate of magnesia and other salts may be made to give very similar discs Chlorate of potass crystallises in square tablets; nitre in long thin prisms which appear as a network of coloured threads To get this latter effect the solution must be rather dilute, and after the disc is covered, all the solution that will go, jerked off; then left to evaporate in the cold. Most of the salts may be mounted in balsam, choosing the best positions before fixing.

Another class of beautiful crystallisations is formed by *melting* the substance between two glass plates. Make a pai of spring-wire forceps, like Fig. 175; then put some of the chemical between two clean plate glass discs, and hold in the forceps over a spirit-lamp: or over the chimney of an Argand gas-burner is not too hot for some. Care, of course, is needed not to crack the glasses. Most of the substances that crys tallise well in this way are of the "organic" class, and some require a very thin film, which must be obtained by putting down the two hot glasses on a blotting-pad, and with thick padded gloves working close together till the film is nearly ready to set. The following I have found to make fine slides in this way:—Cinnamic acid (gentle heat, *very* thin); succinic acid (rather strong heat, very thin); cinchonine (moderate heat and thickness); santonine (fair thickness). This last gives very various effects, some slides showing a rough "ferny" pattern, while others are smooth in appearance. The most brilliant of all in colour, however, is benzoic acid, and it is also the easiest. It usually crystallises in long straight crystals; but with a thinner film and very flat glasses I have obtained exquisite "ferns."[1]

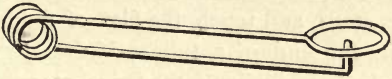


FIG. 175.—Spring Wire Forceps.

Benzoic acid is especially convenient for a beautiful experiment. It melts at very moderate heat; and by preparing a wooden frame into which the double glass plate can be slipped and secured by a dovetailed slide while still hot, crystallisation may be shown *proceeding upon the screen.* The effect, as the crystals shoot out in the most gorgeous colours, is exceedingly

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[1] Micro-crystallisations, as a rule, do not answer for the lantern polariscope. The microscopist only requires perfect crystals on a small scale; whereas, on the screen, these hardly show, except with the greater power of the polarising lantern microscope, which will exhibit them brilliantly. For the low power here considered, we want a much larger "pattern," and brilliant colour, even at the expense of what a microscopist would call coarseness, but which with low power does not appear so. Many beautiful crystals are available for the microscope, such, for instance, as the platinocyanides, and can be purchased in immense variety for a shilling each. Quinate of quinine and quinate of lime deserve special mention as exquisite micro-crystals. Many of these can be shown by the simpler micro-attachment described on page 252.

beautiful. Cinnamic acid and the others crystallise with the same facility, but it is difficult to get the right thickness to show colour with them, while benzoic acid never fails. Another experiment of this sort is to place between two warm glasses a saturated *boiling* solution of silver nitrate. As this cools crystals form. The same slide when heated will re-dissolve the crystals, and is then ready to repeat the experiment. Another method is to warm in a test-tube a strong solution of urea in gum-water, pour it over a *warmed* glass disc which is placed in the stage, and touch the film of fluid with a small crystal held in the end of a tube. If the strength is right (which seems however difficult to arrive at sometimes), this crystallisation is very fine. For the polarising microscope slides are prepared specially for this purpose, of several of the fatty acids. These have simply to be warmed; when the crystals melt, crystallising out again as the slide cools, the same slide lasting for scores of experiments. One or two of these acids are coarse enough for the large glass discs of the lantern polariscope.

155. **Mineral Sections.**—The majority of these, consisting as they do more or less of crystalline constituents, exhibit beautiful chromatic phenomena in the polariscope, which is indeed the most powerful instrument of the petrologist. A petrological microscope is usually fitted, not only with a polariser and analyser as usual, but with a quartz plate which can be introduced at pleasure over the objective (the use of which will be understood from the next chapter) and a system of convergent lenses for exhibiting the phenomena described in Chapter XIV. The phenomena can be seen in a portion of the section even the tenth of an inch square. All the varieties can be beautifully shown upon the screen by aid of the polarising projection microscope; but for the lower power of the ordinary polariscope, only the bolder and coarser sections are on a sufficiently large scale to be distinguished clearly. Such a selection will be found in granites, perthites, agates, zeolites,

labradorite, or any mineral similarly coarse in details. Such a simple microscopic power as described on p. 252 extends the list much. Some minerals should, if possible, be cut different ways to show variation in the consequent phenomena. Thus, what is known as "graphic" granite gives the usual appearance cut in one way; while cut in another plane it exhibits a sort of marking like an oriental inscription. And labradorite may be cut so as to exhibit mere colour as a film; or straight coloured stripes, or bands of rotational colours (p. 323).

156. **Organic Structure.**—We have seen that the double refraction in films, and the interference colours we are able to produce from it, are due to a greater and less elasticity in two rectangular planes. Nearly all *organic* tissues or substances present this structure, or have a decided "grain," as it were. We used a piece of board as an analogy (§ 148). Hence all such structures "polarise," and a thin longitudinal section of wood, if transparent enough, behaves as a film of crystal on the polarising microscope. It will be understood without explanation, from what has gone before, that the greatest depolarising or colour effect is obtained when the "grain" of such a section is adjusted at an angle of 45° with the plane of polarisation.

This property of organised structure is of the greatest service to the student of histology. Sections of tissue which appear to ordinary methods perfectly transparent and devoid of detailed structure, by these differences in elasticity and consequent refractive power in certain directions, make structure conspicuous to him, when he examines them in his microscope by polarised light. He is constantly using this powerful means of analysis, which reveals to him what would otherwise be hidden from his eyes.

A vast proportion of these phenomena can also be exhibited on the screen by a good polarising projection-microscope; but for ordinary lantern demonstration we may make a limited selection of the coarser objects. A quill pen thus placed in the stage shows beautiful fringes of colour; but it is better to cut off the barrels of two pens, slit them both up on one side, and boil for an hour or two. They then become quite soft, and can be rolled out and dried flat between two glass discs, which they nearly cover, and make a fine slide. So does a sheet of horn, such as is used for stable lanterns, and which can be bought for a few pence. So will a piece of bladder, if of the right thickness to come within the colour-limits; or a few large fish-scales or gill plates. The shoulder-blade of a rabbit may be scraped rather thinner and mounted, or the "bone" from a lobster claw. Shrimp or prawn shells, soaked in turpentine and then mounted in balsam, polarise well. If the thickness is not quite right for colour, this can be brought out by a superposition film.

157. **Effects of Strain or Tension.**—If double refraction and its consequences be really due to unequal elasticities, we can readily demonstrate the fact by subjecting to unequal stress substances which in their natural state are homogeneous, and therefore show no double refraction. Thus, annealed glass, being of equal elasticity in all directions, does not polarise; but by making the elasticity unequal, it should easily be made to do so. Make a brass frame like Fig. 176, the size of the wooden slides, with a square-headed screw by which, with a T-handled key, strong pressure can be brought to bear through the centre in one direction,[1] the glass abutting against a convexity, A, opposite the screw, and being protected from the grinding of the screw by a convex padding, C, of brass or copper. At the least touch of the screw double refraction is shown by fringes of colour, and as the strain increases the effect is gorgeous

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[1] Such pressure-frames are usually made by opticians of wood, with a thumb-screw, and flanges to keep the glass in place. But the chromatic effects heighten with the pressure; and as the glasses only cost about 2*d*. each, I prefer the T-key, and "put on" all I can, usually till I break the glass. The effects are far finer with this extra power, and best just before the smash comes,

beyond description. Then let the glass and frame be turned to 45° angle with the planes of polariser and analyser. The effect now is totally different, but equally beautiful. Next put in two bits of copper or brass, B B, in the corners of the frame opposite the screw, and abutting against them an oblong piece of glass. The strain now is different, resembling the breaking-load of a bridge. It will be seen how the coloured figures also differ, and how exactly the "lines of strain" are optically represented on the screen.

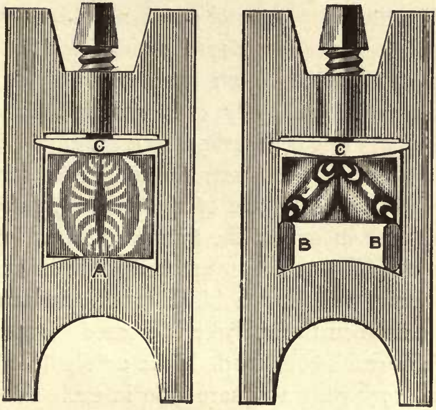

FIG. 176.—Screw Press for Glass.

Other transparent substances will give the same effects. A glass trough, made the size of a slide, open at one end and filled with clear cold jelly, will show beautiful phenomena if a rectangular piston is pushed in at the end so as to compress it. So will a glycerine "jujube," if compressed in any manner; but a still better plan, if a slab from which the lozenges are cut can be obtained, is to tie back the studs of the optical-stage, pass the slab of elastic matter through, and *extend* it with the two hands, of course at an angle of 45° with the polariser and analyser. A strip of thin transparent india-rubber will show similar phenomena when stretched. If neither is handy, soak some gelatine in cold water for a few hours, and then melt it with about two-thirds its weight of glycerine, and pour out upon a smooth stone or iron slab, greased, to cool. The composition will be something like that which printers use for their rollers, but clearer; and an oblong slab passed through the slide-stage (kept clear by tying back the studs), and stretched, gives beautiful colour phenomena. Not much time must be wasted over such jelly, or it will melt with the heat of the lantern, unless this is absorbed by a water cell.

Heat applied to glass produces the same effects, owing to its expansive powers. Even one of the plain glass discs, fixed with a spring wire in one of the frames and held momentarily on alternate sides (so as not to crack it), with its centre over a small spirit-flame, will show a black cross, and transmit light through the rest when the analyser is crossed. But much better effects than this can be obtained. Make a "shell" of sheet-iron, like A B, Fig. 177, with a square hole in each side, 1¼ inches square, the parallelogram measuring 4 by 2¼ inches, so as to go in the slide-stage. A little bit turned over from top and bottom at A A, one end, makes a "stop" for adjustment. Cut a piece of wood, C C, such size and shape that the edge of one of the thick glasses made for the press just described, "jams" into the shallow notch, and when wood and all are pushed in against the end stop, A, the glass stands central with the apertures. Fit a small bar of iron so as to slide in over the top edge of the glass. Having adjusted all except the bar of iron in the stage, and made the iron a dull red heat, slide it in over the glass; at once fringes of light and darkness, and presently of colour, spread over the screen.[1]

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[1] The private student needs no expensive apparatus for this class of experiments. As a boy, many, many years ago, I first made the above experiment in the following manner. A dinner plate was inverted on a bare polished mahogany table, and on this was laid a rather massive square bar of heated iron. On this was "stood on edge" a 2-inch square of plate glass,

In glass made red hot and *suddenly* cooled, these beautiful effects are permanent. Such are called chilled or unannealed glasses, and cost from 4*s.* to 7*s.* 6*d.* each, of various sizes and patterns. In making them, the great thing is to cool rapidly round the *edges*, and to start with a red heat. A square block made red hot, and stood on one edge on an iron smooth surface, while any mass of smooth metal is balanced on the top edge, will after cooling show very good phenomena, especially if slid on to fresh cold surfaces till cold. A good chilled glass gives coloured figures particularly vivid, and the figures can always be foretold. The most instructive shapes are a circular

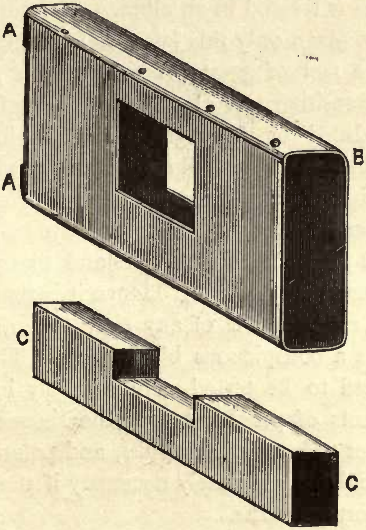

FIG. 177.—Apparatus for Heating Glass.

its edges ground flat on a stone with sand and water. The table acted as polariser, and a few slips of glass placed in the card case of a medicine-bottle, as analyser. I do not think I have ever experienced such pleasure from any experiment since, disc, which naturally gives circular rings, and when the analyser is crossed a black cross; an oval, which yields very similar effects to a bi-axial crystal with convergent light as described in Chap. XIV., and a square. This latter appears as at I, Plate IV., when polariser and analyser are vertical and horizontal; if these are then rotated 45° (but still crossed) the colour and fringes are as shown at J in the same plate; or if the chilled glass is rotated in an elbow polariscope, the figure is the same in the glass, only this latter stands diagonally.

This too is a fact of great practical value, polarised light being a most sensitive test of any lack in perfect annealing. A "Rupert's drop" or "Bologna flask," for instance, shows conspicuous phenomena, as will almost any glass paper-weight, inkstand, or other massive piece. A section of very thick glass tube, ground flat and polished, almost always makes a beautiful slide; and this prepares us to understand that perfect annealing is by no means easy to get. Hence it is that a great many optical *lenses*, especially if of any size, too often exhibit in the polariscope a conspicuous black cross. The lenses of a polariscope need to be tested very carefully indeed; but in other instruments of precision also, the inequality of refraction is sufficient to impair the results, and polarised light thus becomes an analyser absolutely necessary if the instrument is to yield trustworthy results.

158. **Stress in Liquids.**.—By bringing terminals from a powerful Wimshurst machine to within a small distance of each other in a piece of glass, by holes drilled from its surface, Dr. Kerr demonstrated that, as we should expect, a powerful electrostatic charge acted very much in the same way as mechanical compression—that electric stress had much the same effects as mechanical stress. But he further demonstrated that it was the same with a di-electric fluid! He placed next the polariser a glass cell containing carbon bisulphide, in which was immersed two copper plates facing each other at a small distance —say $\frac{1}{8}$ to $\frac{1}{2}$ an inch—so that the plane-polarised beam passed

between the plates, and constituted the field shown on the screen. The plates were made the terminals to a powerful machine or Leyden jar, and charged, polariser and analyser being arranged for the dark field, but so that their planes stood at 45° angle with the line from terminal to terminal. At once light, and generally coloured light, flashes upon the screen, as if the fluid in the space between the terminals were a piece of strained glass.

This may at first seem a matter of no particular significance, but in reality it is of the deepest. For this one fact alone amounts to absolute demonstration, that the phenomena are not essentially due to any merely mechanical stress in particles of matter, but that the *real stress is in the ether.* We can cause stress in solids or in jelly by mechanical means; but by no mere mechanical pressure can we produce stress in a fluid, which by its very constitution distributes the pressure equally in every direction. Yet a stress is produced here by the static charge; and the fact is clear proof *that it is the state of the ether* which is the essential matter in the phenomena of light.

159. **Effects of Sonorous Vibration.**—By this time we have a very vivid idea of the subtle power of polarised light as a revealer of the inner structure or molecular condition of bodies, provided they are transparent enough to apply such a test. The slightest difference in elasticity, or density, or, in short, from a homogeneous condition, at once stands revealed before this searching analysis. A singularly beautiful experiment, which Daguin describes as first made by Biot, though Dr. Tyndall first exhibited it by the lantern to a public audience, will show this power in a still more striking light. Get a strip of plate glass 5 feet to 6 feet long, 2 inches wide, and about $\frac{1}{4}$ inch thick, and smooth the sharp edges with a stone, or with a file and turpentine. Prepare for it a wooden vice, fitting into one of the wooden stands so often used, and thus adjustable for height; and in this let the exact centre

of the strip be fixed[1] at an angle of 45° with the plane of polarisation.[2] Draw forward the slide-stage, power, and analyser some little way in front of the polariser, if a direct polariscope; or if of the elbow form, unscrew the slide-stage and objective from the elbow, leaving only the elbow on the lantern, and support the "front" on a wooden cradle of some sort (easily made by cutting semicircles out of the ends of a cigar-box) in its proper position axially, but leaving a clear space of an inch or so between the parts which ordinarily screw together. Through this interval pass the glass strip, and adjust the height, &c., so that the strip may cross the field as near the middle point held in the vice as possible. Cross the analysing Nicol to give a dark field, and throw a loose cloth on the "front" so as to stop all scattered light as much as possible. (Half the battle in *all* lantern experiments, especially with an inferior illuminating power, is to avoid such scattered light, and many operators lose much effect by not attending to it.) Now take a wet *flannel* cloth (other kinds "bite" the glass too much and drag the vice about), and enveloping the free end of the strip in it, rub it smartly up or down with a long smooth sweep. A shrill but wonderfully clear musical note sounds out, from the longitudinal vibrations into which the glass is thrown, and at each note the dark screen is illuminated! If now a "chilled" glass be placed in front of the optical slide-stage, and focussed as usual, and the experiment be repeated, at each note a quite different *colour* appears; or if a selenite butterfly be inserted, some other colour of that will appear. Or we may vary the experiment by putting in the arrangement for heating glass. Starting with a dark field, on inserting the

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[1] It is well to glue on the inner side of each jaw of the vice a circular thin slab of cork, so as to give a good pinch without breaking the glass.

[2] If the polariser is a Nicol, or either of the Delezenne forms, it is in some respects more convenient to set the polariser and analyser at 45° with the horizon, when the glass can be horizontal, and pinched at right angles.

hot iron bar we get the phenomena varied by the effects of *heat*-vibrations; and when we have got good colour, we vary these again by interposing *sound*-vibrations. The experiment can be very fairly performed with even an Argand burner, at a screen distance of about 4½ feet, giving a disc of 15 inches.

This beautiful phenomenon is due to the stress caused in the glass near the nodal points, by the vibrations into which its molecules are thrown. Here, however, a difficulty may occur to some solitary student which actually did occur to myself, and which led me for some time to question this explanation. Dr. Tyndall himself states[1] that, upon sounding the glass, the screen effects are rendered "complementary"; and in my own experiments I generally found this to be the case. The change from mere darkness to light only, is easily accounted for on the supposition that the thickness of glass, or the double refraction and consequent retardation, are not enough to produce colour; but when selenite designs give also "complementary" colours, the supposition naturally arises that the change of phenomena is of some *absolute* kind, and not one of *degree*, or comparison, as we should expect from a state of stress. Accordingly, I was for a considerable time inclined to attribute the phenomena to the half-wave retardation (§ 150) caused by the mere "resolution" of the plane-polarised ray, by the "absolute" motions of the glass molecules at an angle of 45°. But a valued correspondent[2] subsequently placed in my hands a translation of the researches of Kundt and Mach into this subject, which clear up the matter by showing that there *is* degree or variable amount, in the effect produced; and that therefore the "complementary" results must depend upon the strip of glass giving an average retardation of about half a wave length.

Kundt having sent the light through the apparatus as described, analysed or spread into it a long band of light by a

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[1] *Six Lectures on Light*, second edition, p. 137.

[2] The Rev. Philip R. Sleeman.

revolving mirror. This band was broken like a string of pearls, showing that the doubly refracting effect was periodic, and coincident with the sonorous vibrations. Kundt then further interposed a selenite plate giving bright colour. The light being analysed as before by the revolving mirror, the band was found to *vary in colour*, the number of tints observable in the band increasing with the thickness of the glass or the intensity of the vibrations. Even thus, therefore, was established the degrees in double-refractive effect which the hypothesis of stress required.

But Mach carried the investigation still further by means of spectrum analysis. Selecting a selenite which gave at least two or three dark bands (§ 153), the light which passed through it and the glass bar was projected through a slit and prism as usual. When the bar was sounded, the dark bands became of course confused, and disappeared. But, assuming the slit and prism to be vertical, and the spectrum therefore horizontally dispersed, this spectrum was compressed into a narrower and more brilliant one by a cylindrical lens whose axis was horizontal, and then again dispersed vertically by a rotating mirror whose axis was also horizontal. Every colour and dark band was thus drawn out into a vertical string; and when all this was adjusted, the dark interference spots thus spectrally analysed separately, at successive moments during the sounding of the glass, were found drawn out into *zigzag curves*, whose amplitude represented the shifting of the bands, by the additional retarding effects of the temporary states of stress.

This beautiful experimental analysis places the true nature of the phenomena beyond any doubt.

APPENDIX TO CHAPTER XII

Manipulation of Mica-Film Work

The necessary implements for mica-work are few. We need first a thin, smooth, and broad paper-knife of ivory or tortoiseshell, carefully thinned down at the end to nearly a knife-edge. One or two very sharp needles will be required, and a few stronger points in handles of some kind for marking-out; or a steel stiletto such as accompanies sewing-machines answers well for the latter. For cutting, provide a strong pair of scissors with not less than four inches clear cutting edge, and a small pair, of the dissecting type, with pointed blades an inch long. These must be carefully *smooth*-sharpened on a small stone, as required, which will however not be often: on the other hand two or three good pen-knife blades, or surgeon's lancets, for thin film cutting, will need sharpening constantly. For cutting circles I use pen spring-bows, breaking away one half of the pen and carefully sharpening the other, also the steel point on the other leg. The only other necessaries are a pair of forceps (which I prefer to be ivory-tipped), a few of the usual drawing instruments, a graduated rule, and a cutting straight-edge. For the latter a small steel rule will do, or the edge of a microscopic glass slip. I have already mentioned the "doubler" polariscope shown in Fig. 169.

Besides a slab or two of mica, which has been sufficiently described, there will be needed some Canada balsam dissolved in benzol, and a little gum Arabic. The latter must be the finest perfectly white gum, kept in a capped bottle with a small sable pencil. The balsam should be the palest procurable, and is prepared by drying in a slow oven till it is as hard as pitch and will chip into flakes; when it is dissolved in the best benzol. The solution is well known to microscopists, and can be purchased, or the dried balsam can also be procured. It is best to have two capped bottles of the fluid, one as thin as cream, the other like a thick syrup.

The first step is to split up a lot of mica, for which a portfolio with leaves, or a large thin book, will be a handy receptacle, as the films should be kept classified. The mica will probably be in slabs from $\frac{1}{8}$ inch to $\frac{1}{4}$ inch thick, and "even" films cannot usually be split off direct. The first step is to split it into two, and then into four, and so until it is all split into layers as thick as very thick card. This is done by first "starting" the edge with one of the strong steel points, then inserting the paper-knife, and gently coaxing that in further and further, with now and then a little twist to help in starting it apart. The more slowly and gently all this is done, the more chance of getting any of these primary surfaces even and unbroken. In doing it, now and afterwards, the knife will appear to scrape or scratch the smooth surface somewhat, but this is of no consequence whatever, as every such mark totally disappears when in contact with the balsam and benzol. The layers should be thus split down till they just begin to show faint traces of colour when examined with a Nicol, and then laid together again in the position they formerly occupied in the original slab.

Each layer should now be examined carefully with a Nicol, by daylight from a window, over a large polarising surface such as a mahogany table, or plate of glass. The object is to see all inequalities of thickness, where in splitting the surface may have broken through, and a very minute difference of cleavage occurred. With the Nicol at the eye, these will show differences of colour, the boundaries easily identified with fine hair-lines visible on the surface to close scrutiny. Where a surface is much broken up in this way, attempt should be made with great care to split off a thin film from it, to get an even surface: some original surfaces will be found good. Absolutely *all* of a plate is rarely found even, and when the greater part is so, the operator had best be satisfied. There is a great difference in pieces : a good piece of mica is a prize, while one that persistently refuses to split evenly, may as well be abandoned.

Marking the Mica.—The next and most important step is to mark the pieces, to show the polarising planes. Choosing one of the thinnest and most even, "the doubler" is arranged before a window at such a distance as to get the best polarising angle, and carefully adjusted so that when the analyser is crossed, the darkest part of the field appears as a dark nebulous patch in the exact centre of the mirror at the bottom, which is marked with lines as in Fig. 178. Some care should be expended upon this, and also, by turning the analyser a little each way, to train the " eye " to recognise any *slight* tendencies of the dark patch to travel either right or left of the centre. Then the sheet of mica, or one end of it probably, is laid on the mirror and carefully orientated by hand, until no colour is seen, and the nebulous patch *occupies its exact central position as before.* The positions are now known ; and if a straight-edge be laid over the line *ab* or *cd*, and a bold scratch struck, it will give one of the polarising planes of the mica ; or *ef* or *gh* give the lines which, placed parallel with the polariser, give colour effects.

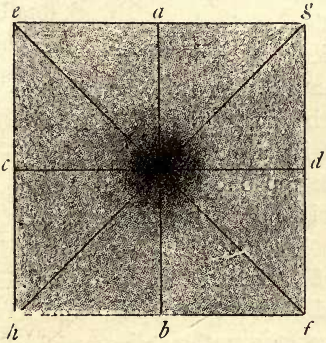

FIG. 178.

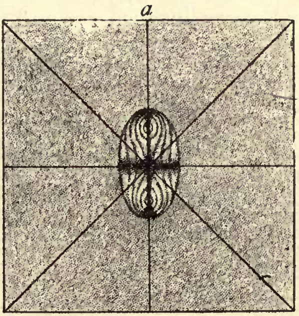

FIG. 179.

Much time and care should be given to this marking of the first or "key" plate. It is well to make a number of observations, marking each with a different scratch, and moving the mica between each into a different position—then making a final deep scratch as the mean of the results, if there is any difference. Sometimes, instead of using a straight-edge over the lines on the mirror, it is more convenient to strike the axes by laying a broad parallel rule close up to the sides *eg* or *gf* of the box, or the other lines by similarly using an ordinary mathematical 45° square. There is a still more accurate method of finding not only the axes or planes, but which of them is the *principal* axis. Laying on the mica-sheet, half of such a convergent lens-system as described in § 190, with a suitable focal lens near the analyser, the system of rings shown at D, Plate VI., will appear. The mica should then be so adjusted on the mirror, that when the analyser is exactly crossed, the long black brush lies exactly straight along the line *ab* as in Fig. 179. This line *ab* is then the principal polarising axis or plane of the mica.

Splitting Thin Films.—The mica-sheets having been preserved in due order, every one can now be marked in succession from this key-sheet. The next sheet is laid over it, so that the edges precisely coincide, and the top one scratched over the scratch lying beneath. The next is laid on that one, and so on, till all the sheets are marked. When that is done, all bad and frayed edges are trimmed off each sheet, down to smooth good mica, with the scissors. And when that is done, the mica is further split down with the greatest care to the various approximate thicknesses desired. This can be done, it will be found, much better from the thinner sheets, with their trimmed and sound edges. The sheets should be laid on several thicknesses of smooth paper, and the paper-knife used with the greatest gentleness, firmly held down to the flat beneath, while it will somewhat bend upwards at the handle end. As the films become very thin, the split will need to be started with one of the finest and sharpest needle-points; and to insert even that, it may be necessary to slightly thicken the edge, by rubbing it with the smooth side of the needle.

As each film is separated from its fellow, the marking must be repeated on it, making the scratch no deeper than is clearly visible. Every film is also to be carefully examined for evenness, and any uneven portions plainly scratched at the boundaries with a needle-point; while the differing part of the surface should be defaced by scratches, unless large enough in area to be used on its own account. The films are finally sorted into the book or portfolio, and marked (if known) as what they are, ready for use.

The thinnest film of any real use is what is called an $\frac{1}{8}$-wave film—that is, in passing through it the ray traversing one plane is retarded behind the other by one-eighth of a wave. Such a film is exceedingly thin, but every endeavour should be made to procure one at least, wherewith to construct the Fox wedge already described, shown in Plate IV. at A.

Gauging the Films.—This brings us to the very important point of *gauging* the films. Here especially the Fox wedge is invaluable; as such a preparation, once made and verified, instantly gauges any other film adjusted to "cross" it. The stripe that is black, (with the dark field) gives the thickness; or if two stripes are equally dark and not quite black, the thickness lies between them. We easily gauge these all-important $\frac{1}{8}$-wave films by the "doubler." It is plain that if we superpose two films the same way, and lay them on the mirror with the principal axis at 45° (*i.e. ef* or *gh* in Fig. 178), they will be in the depolarising or colour position, and amount to *a quarter* wave. The "doubler" itself doubles this, making a *half* wave (and of course one single quarter wave plate, as mentioned further on, is gauged just the same). And the crossed analyser (see § 150) *gives another half wave*, making a whole-wave difference. But this restores coincidence and means perfect transmission; while the *half* wave retardation resulting when the analyser is parallel, means extinction (all but the plum-colour caused by the slight residuals already spoken of). Therefore if two films thus laid on the mirror, give this "tint of passage" when the analyser is parallel, and it is known by that "feel" of the film which is speedily recognized that the thickness does not belong to the second or third orders, they are known to be $\frac{1}{8}$-wave films, or a single film is known to be a $\frac{1}{4}$-wave. Many approximately $\frac{1}{8}$-wave films may be split before one *true* one is found; and it is desirable to test this even more severely by superposing *four* of them (a very small square is enough for this) with a drop of the balsam between to render them more transparent. The four will give the *second* tint of passage, and make the matter sure.

Cutting the Films.—This is done differently, according to their thickness and character. Thin films, from $\frac{1}{8}$ to $\frac{1}{4}$, which have to be cut *exactly*, are best handled as follows. Prepare a sheet of cardboard about 16 × 12 inches with the black varnish described on p. 18, lay it on an accurately-squared drawing board the same size, and fix the film to the board through card and all with drawing-pins, at the two top corners, taking care that the scratch marking the axis of the mica which is to stand vertical, lies accurately on the board to a T-square. The pieces are now carefully drawn with steel point. For the 24-film wedge, the simplest plan is to rule the whole film off into horizontal bands $\frac{1}{8}$ inch wider than the length of the stripes to be shown, and with a narrow strip or space rather more than $\frac{1}{8}$ inch wide between the bands. Then the longest film is measured and scratched on a band, allowing $\frac{1}{8}$ inch longer than is to appear. The second film will be *one eighth* of an inch shorter (because $\frac{1}{16}$ inch at *each end* of the longest film will be blacked over, while every subsequent film will mark the edge of a stripe at one end). Every film after that will be *one-sixteenth* of an inch shorter than the preceding. When all are scratched out with the point, one similar corner on each is lightly marked to ensure all being superposed the same way, and the bands are cut apart with the scissors up the narrow spaces purposely left. But the rest, and all exact cutting, must be done with penknife blade or lancet. Laying the cutting straight-edge *exactly* to the scratched line, the blade is moved backwards and forwards with a very light pressure indeed, keeping the edge perfectly in line, till the piece separates. The hard black varnish both gives the very best backing to resist the cutting-knife, and enables the scratches and all that is done to be best seen. All precise work is thus drawn with steel point on the mica, and cut with a single blade to a straight-edge, in this manner. Similarly with circles: the spring-bow compass, with half a steel pen as cutter, is revolved repeatedly with a very gentle pressure, till the disc separates. The slight thickening of the edges caused by this method of cutting is of the greatest service in all "fitted" work, by preventing these thin films from sliding underneath the edges of their neighbours.

Mere geometrical patterns in thicker films are better handled differently. The patterns desired, such as those shown in Plate V., may be drawn carefully and distinctly in ink on white card, which is further ruled with vertical lines an inch apart all across it. The mica being fixed to the board through this card as before, with its intended vertical axis parallel to one of these lines, the required pieces are carefully traced over the drawing by means of the steel-point and straight-edge, a key corner being marked on each before the piece is cut loose. In going through a design like any in Plate V., the mica film will be cast loose and shifted along for each successive piece; hence the convenience of a number of vertical lines, to any one of which its axis may be laid. Then the rough area of each shape is first separated with the large scissors, and finally the shape cut to the scratched lines with the same. Cutting over the blackened card, it will be found that what is done can be readily seen. Shapes which present interior angles, such as those forming the octagon star shown at D, Plate V., are cut round nearly close to the outer points with the large scissors, and the interior angles carefully cut out with the small pointed ones.

The method of design is a matter of choice and convenience. Mr. Fox, who first executed any work of this kind, put all his patterns together with pieces of different thickness, fitted like a mosaic. I found this process exceedingly difficult, while it did not satisfy me in range of colours; and therefore devised a method which in my hands proved both easier and superior in effect, viz., designing patterns which allowed of the *superposition* of geometrical shapes, gradually decreasing in size as a rule, but not necessarily. Plate V. gives sufficient examples, of which details are given further on. The contrasts of colour obtained by thus employing successive *orders* of colours, is much finer, if the films are judiciously gauged. As the first few bands in the wedge give no colour, it is best to start with a full-sized disc of mica as a foundation, about $\frac{5}{8}$ thick, where colour practically begins. Then if the succeeding "pattern" films range from a $\frac{1}{4}$ thick to about $\frac{3}{8}$ thick, the harmonies and contrasts are sure to be good : but exact $\frac{1}{4}$ waves superposed, naturally give a rather monotonous effect.

Cementing and Mounting.—For mounting in the usual 4 × 2$\frac{1}{4}$ inch wooden frames, glass discs slightly over 1$\frac{3}{4}$ inch diameter, are most convenient for ordinary preparations; but the 24-film wedge, if the stripes are $\frac{1}{16}$ inch wide, will need 2-inch discs to lay it down comfortably, and the larger size is better also for some few other preparations. A glass being cleaned, sufficient of the thinner balsam is dropped in the centre from the glass rod, taking care there are no air-bubbles —for a large piece more than one drop will be needed; for a small shape a very tiny one indeed. Then the film to be laid down is taken by one edge in the forceps, cleansed from loose dust between thumb and finger (the greasy marks so caused will all disappear) and gently laid down in position, shifting it a little if required by a couple of steel-points, pushing at opposite edges. The axis of any "foundation" film the size of the entire glass must be plainly scratched, and the first "pattern" film very carefully laid to this and adjusted centrally; each subsequent film of the pattern will be laid as a rule to the points of the film underneath. This will need care, holding the film below steady with one point, so as not to alter adjustments already made, while the last put down is adjusted to it in turn by another point. The balsam should run nearly, if not quite, to the points or edges. When all are laid down, before the top glass, or a quarter-wave film, or anything covering the whole, is cemented down upon the preparation, the latter should be put aside for at least a week, protected from the dust by an inverted tumbler, for the balsam round the edges of each layer to become dry. This is essential, to prevent the films from slipping out of adjustment when the cover glass is pressed down.

The Fox wedge will need special handling. For very thin films, like $\frac{1}{8}$-wave, the balsam also must be very thin. The largest film has only to be laid down on the centre of the glass disc, and whilst the films are long enough to be distinctly oblong, it is best to lay rather a streak of balsam, as it will thus spread out better. The second film is then merely laid even with what is to be the thick end of the wedge, the other end of it marking the first stripe. It is well next to fix the glass in a frame by a couple of morsels of putty, so that this stripe is parallel to a small T-square laid across the frame. And the successive films are laid down so that their ends coincide with the divisions on a rule laid along over the wooden frame from time to time, not in contact with the mica. The films are easily adjusted by steel points so long as the balsam is thin and moist; but it must be done then, as it soon begins to set round the edges.

The most delicate adjustment of all is required when the small parts of a preparation in thin mica, such as the quarter-waves shown in Fig. 188, have to fit accurately edge to edge. At first they *will* slip under each other; but the thicker edges caused by the knife help much, and after a few trials it will be accomplished. It is in these very precise preparations that *gum* is useful. Colourless gum is practically invisible, and when these delicate preparations, or any parts of them, are successfully laid down, a very tiny drop of thin gum may be taken on the point of the sable pencil and introduced under two points of the piece. When "run in" the gum should not occupy more than $\frac{1}{16}$ of an inch square. For a moment or two the film may still be moved if necessary; but the gum rapidly dries, and that piece is then *fixed*, as the gum is not at all affected by the thin balsam afterwards added, as dried balsam is. With wedges, the balsam will rarely spread at first to the outer corners of the successive films, and the best plan is, when all are laid down, to draw a narrow streak of the thin gum all along the top and bottom of the wedge, which will run a little under each corner. All is then left to dry as before.

After some days the cover-glass may be put on. The disc should be laid on something rather smaller—a pill-box or short piece of brass tube will answer well—and sufficient balsam be dropped on to the centre as speedily as possible. Then the cover is laid down very gently and accurately, so that it may not have to be dragged about. The balsam will "run in" to any points not quite filled, as it reaches them in extending outwards, and should nearly reach the edge of the glass. Any bubbles should be pricked before laying the glass on. Some small bubbles may occur from little dry spaces left between the films; but if the balsam is thin, all but large ones will gradually disappear of themselves. Finally, a weight of about half an ounce, with a flat bottom, is laid on the centre of the top glass. This will probably squeeze some balsam out at the edges—hence the need of a smaller support underneath. If any considerable space is left, a little balsam applied at the edge will readily "run in," in most cases.

With all possible care there will be a good percentage of failures, which is disheartening if much trouble and labour has resulted in a specimen apparently very successful up to that point. Obstinate large bubbles *will* occur, and it is almost impossible to get them out. They are easily enough moved outwards and excluded, by squeezing the glasses together; but the thin balsam rapidly re-dissolves the dried balsam on which fixity depended, and the films slip about also and spoil the slide, in nearly every such case. Practically, very little if anything can be done to mend a preparation when the cover-glass is once laid down. It is to avoid such mischances that a little gum is so useful in many cases; but it is rather difficult to use it much without being visible on the screen.

The preparation is left undisturbed under the small weight for a week or so, after which it should be gently baked in heat of about 100° or 110°. If access can be had to a place where there is a steam-engine, a small box containing the objects is well placed somewhere in the boiler-house; or the egg-drawer of an incubator does well. A domestic oven is far too hot, but the plate-rack over a kitchen range is a good place, provided the operator be a *persona grata* to the presiding genius. The baking should occupy some days, looking at the preparations now and then in case any air-space may open at the edge—which may especially happen if too much weight has been used—in which case a little fresh balsam can generally be run in. When sufficiently hard and dry, any loose balsam is scraped off with a knife, and the glasses finally cleaned with a few drops of sulphuric ether on a bit of soft rag.

The thicker balsam is used to fill large vacant spaces. There will be, for instance, vacancies at the top and bottom of the 24-film wedge; and it is better to lay down some thick balsam there, before putting the thin balsam on the mica and applying the cover-glass. The thick solution gives more support, and air-spaces are less likely to run into it. Such a slide as this wedge will have rough or irregular edges to the mica, by the way: and after it is finished and cleaned, the superfluous area, to the circumference of the disc, is blacked out on one of the glasses with photographer's black varnish.

These are the methods I have found best in constructing preparations of this class. Failure at first is almost inevitable—more or less is likely to occur always; but the beauty of the phenomena, and their clear instructiveness, amply repay the student when success has finally been achieved. Such preparations cannot be hurried, and a month is required to carry one through; but most of this is occupied in waiting. The manipulation itself does not take very long, and the similar stages of several preparations can be conducted at the same time.

CHAPTER XIII

CIRCULAR, ELLIPTIC, AND ROTARY POLARISATION

Composition of Vibrations into Circular Orbits—Quarter-wave Plates—Other Methods—Fresnel's Rhomb—Plane and Elliptical Composition—Rotational Colours—Circularly Polarised Designs—Waves of Colour—Contrary Rotations—Effect of Polarising and Analysing Circularly—Spectrum of Rotational Colours—Phenomena of Quartz—Right- and Left-handed Quartz—Quartz in circularly-polarised Light—Use of a Bi-quartz—Rotation in Liquids—The Saccharometer—Other Rotatory Crystals—Electro-magnetic Rotation—Optical Torque—Rotation or Torque of Common Light—Reusch's Artificial Quartz—Rotation and Molecular Constitution—Effects of a Revolving Analyser.

160. **Composition of Vibrations.**—We have hitherto chiefly considered the resolution of plane-polarised vibrations, and its chromatic effects. We have now to consider the results of compounding them. We have seen that two plane-polarised rays vibrating in the planes — and |, even though both originally from the same polarised ray, cannot possibly interfere with or quench each other. In *that* way, they can have no relations. But they may act on each other in another way. Let a pendulum be mounted as in Fig. 180, so that it swings on gymbals, G, from two axes at right angles to each other;[1] if swung on one axis the bob will vibrate in the path A B; if

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[1] The illustration in this form is, I believe, first due to Professor Baden-Powell.

on the other, in the path C D at right angles with it. Let these represent two rectangular planes of plane polarisation, and the bob a molecule of ether, and let it have arrived at B in the plane orbit A B. It has therefore reached the limit of its swing, and the next moment will begin to swing back, but at this moment has no motion. Just at that moment, then, imagine the bob of a duplicate pendulum, moving in an orbit at right angles to A B, and in the full power or exact middle of its swing, to strike against it as represented by the arrow C¹ D¹. This second bob will yield up its motion and come to rest, and may be withdrawn; but its transferred motion thus applied

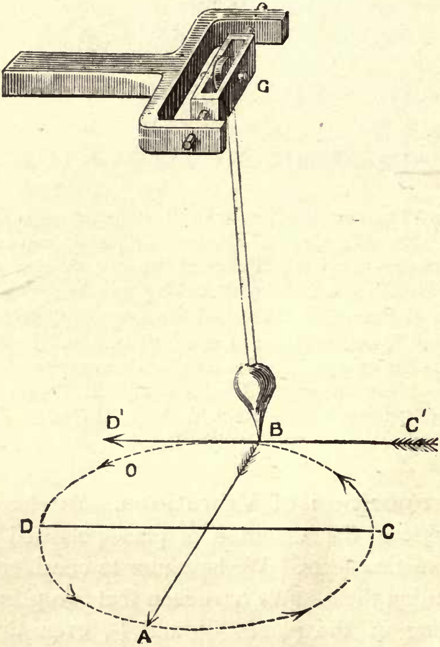

FIG. 180.—Composition of a Circular Vibration.

tangentially, will be compounded with the other, and drive the bob, B, into a new *circular orbit*, B O D A, in the direction of the arrow.

We can see at a glance that the second vibration, to have this effect, must be exactly *a quarter of a whole* (*i.e. double*) *vibration or wave* before or behind the other, or must be at its middle point when the other is at the moment of rest. It follows, therefore, that supposing us to be dealing with actual physical realities—real atoms of ether vibrating in real paths—a circularly-polarised ray ought to result, if we caused one plane-polarised beam to be retarded exactly a quarter of a wave, or any odd number of quarter-waves, behind the other.[1]

161. **Quarter-Wave Plates.**—Such being the theoretical view of the matter, we have already learnt that in several ways we can accomplish such a quarter-wave retardation. The simplest is the use of a thin film of selenite or mica, called a quarter-wave or quarter-undulation plate. It is exceedingly difficult to get a large even film sufficiently thin in selenite ;[2] and therefore mica is usually employed, with which it is very easy to procure one, splitting and gauging the film in the manner described in the last chapter. A film of the proper thickness, when placed in the stage in the position that would give colour were it thicker (the film is generally used in the rotating frame), gives the same illumination as the analyser is rotated, with only a little variation in colour, from a rather bluish grey to a rather yellow or fawn-coloured grey. The reason of

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[1] The student is strongly recommended to work all these cases out by diagram. With a small bat of flat wood as a striker, the effect of two rectangular impulses is readily shown upon a rather heavy ball hung by a string. And the result of the actual compounded motions is readily projected on the screen by a fork or reed apparatus in the manner of Lissajous ; or by a little pendulum apparatus scratching the figures on a slide of smoked glass.

[2] I am not aware of any full-sized quarter-wave plate in selenite being in existence, except one in my own possession, which formerly belonged to the late Mr. J. Darker, and was obtained by a rare accident.

this is, that all the colours cannot be exactly a quarter-wave different, simply because the wave-lengths vary. The test of an equal light will be sufficient for most experiments, if the student cannot undertake the more sensitive and exact test with the Nörrenberg "doubler."

This then is our "quarter-wave" plate, which should be at once mounted between two glasses in balsam, and its working planes marked on the edges by scratching with a diamond or quartz crystal. It can now be observed that all the phenomena correspond with theory; for, placing the plate in the optical stage in the rotating frame, in the proper position it will be seen that a double-image prism gives equal images in all positions; while yet we shall find, by beautiful phenomena of colour when colour-films are introduced subsequently, that the light is still "polarised," though in a different way.

A second smaller quarter-wave film should also be mounted between glass discs, and set in a short bit of brass tube, or a narrow edging of cork, by which it can be fitted at pleasure into the end, B, of the crystal stage shown in Fig. 198. Thus equipped we are ready for a further most interesting set of experiments. Before commencing them, however, we must clearly understand the positions of the apparatus. Representing a quarter-wave plate by Fig. 181, A B and C D are its planes or axes of polarisation, here shown at angles of 45° with the supposed planes of polariser and analyser. This is the position of the plate for producing circular polarisation, in which it should be marked on the edges at E F, G H; it is also the usual position of a coloured film. But in many experiments the plate is used at an angle of 45° with this position, bringing the axes A B, C D vertical and horizontal; the plate should therefore be so marked that either position can be adopted with accuracy.

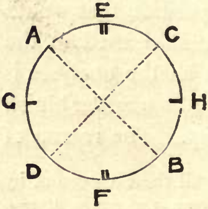

FIG. 181.—Quarter Wave Plate.

For my own use, however, I prefer to permanently mount a large film in each of the positions, making the wooden frame as thin as possible.

It will readily be seen, and must be thoroughly understood by the student, that the whole effect of a quarter-wave film, or any other "compounding" film, depends upon its axes, or planes of vibration, being placed at an angle of 45° with *the last preceding* plane or planes of polarisation. The "composition" which takes place as soon as the rays emerge from the film, is preceded by the "resolution" into two plane rays within the film, which we studied in the last chapter.

162. **Other Methods.**—Light can also be circularly polarised by placing the glass press in the stage, with the screw pressure at an angle of 45° with the polariser, and adjusting the pressure so as to give the necessary amount of retardation. By this method, however, only about one-fourth of the area of the glass, in the centre, gives at all uniform effects, the edges being too strongly doubly-refracting, owing to the greater stress in those regions.

Light is also circularly or elliptically polarised by reflection from metals—almost circularly by silver.[1]

163. **Fresnel's Rhomb.**—Fresnel calculated from mathematical conceptions, that if he constructed a rhomb of glass with parallel opposite faces, so disposed that a ray (A B, Fig. 182) was "totally reflected" twice within it at an angle of 54° 37′ as shown; if that ray was plane-polarised in a plane *inclined at 45° to the reflecting surfaces*, it would be (as it were) so divided and spun round by the relation of the reflecting surfaces to its vibrations, as to emerge circularly polarised; as at C.[2] This

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[1] Light is not plane-polarised by silver at any angle, and circularly only at a certain angle. Hence we see why the silvered surface of the "thin film" in § 105 did not quench the light.

[2] I give this as conveying a rough, realistic idea; in reality, the original ray is divided at the first reflection into two, of which one is retarded $\frac{1}{8}$ of a wave-length; and still more differentiated to a quarter-vibration by the second reflection. The rest follows as in mica-films.

was entirely worked out first in theory; but experiment verified it. The ray *did* emerge circularly polarised; for rotation of the analyser showed no difference in brilliancy, and yet it differed from common light in causing colour, when passed before analysation through doubly-refracting films.

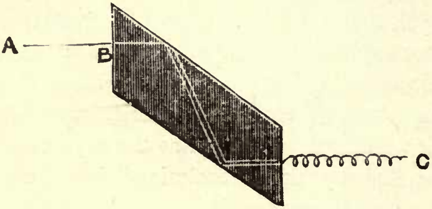

FIG. 182.—Fresnel's Rhomb.

164. **Plane and Elliptical Composition.**—Both pendulums and diagrams will readily demonstrate, that if the compounded rectangular vibrations differ by *half* a phase, the resultant must be another *plane* vibration, at an angle of 45° with them both, but at an angle of 90° with the original plane of polarisation. This is easily demonstrated in fact by a large mica-film equal to the fourth band in Fox's wedge, or half a wave thick. The "dark field" with analyser crossed becomes bright when this film is inserted, and is dark with the analyser parallel. This is another way of analysing the "complementary" effects of a half-wave plate referred to in § 150.

Intermediate differences in phase must result in elliptical orbits. It follows further that with almost any colour-film, much of the light transmitted must, upon emergence, become either circularly or elliptically polarised. With any regularly graded film, such as a wedge or a Newton's-ring slide, regularly recurring bands must be circularly polarised, and intermediate bands elliptically and plane polarised. The usual tests show that this is the case. It likewise follows that any thickness equal to an *odd* number of quarter-waves must give substantially the same phenomena as a single quarter, and an *odd* number of half-waves, of a single half-wave. With any homogeneous light to which the film is adjusted, it is so; but with white light the amount of the *residual colours* which have before encountered us in all interference phenomena, from waves not exactly of the same length, gradually increases with the thickness of the film. This is well shown in the colour modifications of similarly numbered bands in the successive orders of a Fox wedge.

165. **Rotational Colours.**—But we must now study the beautiful optical phenomena which result when a quarter-wave plate is placed in the stage *after* some other preparation which exhibits interference colours. Let us suppose the vibrations transmitted through the polariser are *vertical*. Then we place in the stage a selenite or mica preparation, in the usual position; for simplicity, let it be a simple "even" film. Its axes are in rectangular azimuths at 45° angle with the polariser, and by it the plane-polarised ray is resolved into two whose vibrations are in those azimuths. Next to this comes our quarter-wave plate. For the latter to exert its resolving power in turn, its axes must lie at angles of 45° with the preceding planes or axes—hence those of the quarter-wave film stand vertical and horizontal. They have now to deal, however, with *both* of two rectangular sets of vibrations. What must happen? By diagram analysis we see at once, that each of the first plate's two sets of vibrations is now, separately, resolved into two by the quarter-wave film; that each pair on leaving that film must be "compounded" into a circular orbit; but that these two circular orbits will be *in opposite directions*, and that one of them will have been retarded behind the other, so that the circular motions no longer meet and pass at the exact top or bottom point of the circular orbit, but more or less to one side of it.

Let us see how this will work out when all is resolved and compounded again into plane motions by the analyser. The original plane-polarised ray A B (Fig. 183) is shown here divided into two contrary circular orbits, whose directions are denoted by the contrary arrow-heads at R. Had not one (that resulting from the slowest ray in the first film) been retarded, their meeting-point would always be at either A or B, since from one of these was the starting-point: as it is, the meeting must take place at some other point R, depending upon the thickness of the first film; on which side of the point A depends upon which is the most retarded ray, that depending upon the relations of the planes in the two films. But each circular orbit is compounded of two motions, one being tangential, and the other an equal radial motion at right angles to it (*vide* pendulum experiment, Fig. 180). The two tangential components, shown by S R and T R, meet however in direct conflict, and so destroy each other; and there are now only left the two radial motions, both in accordance, and which therefore unite in the plane vibration R P, which represents a final new *plane* of vibration, or, in other words, a more or less *rotated* plane-polarised ray.

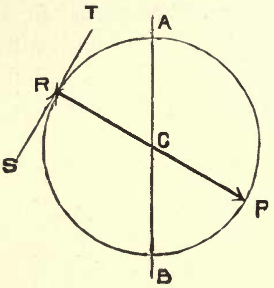

FIG. 183.—Rotation of the Ray.

Thus it would seem to follow, that if we employ a sodium-flame or any other homogeneous light to which the quarter-wave film is adjusted, the analyser, which apart from these films must have been turned to a position at right angles to A B to extinguish the light, must now be rotated to a position at right angles to some new plane R P (depending on the thickness of the first film), but will then again extinguish the light: so that the plane of vibration [1] has been *rotated* through the angle A C R.

Experiment justifies all this to the very letter. It is exactly

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[1] I purposely here use the expression "plane of vibration" instead of "plane of polarisation," because it is the direction of actual *motion* which must be clearly in the mind of the reader.

so: the analyser has to be rotated more or less, and then again cuts off the sodium-light. That is all, so long as we employ homogeneous light. But if we employ white light, it manifestly cannot be all. Here we have all manner of wave-lengths to deal with; and by our whole course of experiments, we have learnt that all these are *differently* retarded, and accordingly their contrary circular orbits cannot all have the same meeting-point R, but these points must follow one another in succession. The analyser must therefore cut off (as it is rotated) one colour at a time in orderly succession of the wave-lengths; and the residuals, as usual, will exhibit gradually changing "composite" complementary colours, passing approximately in turn through all the colours of the spectrum.

This also is justified to the letter; and very beautiful it is. From one to two waves thickness for the first film gives the most apparently complete spectral series of colours; but using any colour-film, either simple, or a geometrical or other design in selenite or mica, on rotating the analyser we get, instead of two complementary colours, and two positions with no colour at all as heretofore, all the colours passing into each other in beautiful succession.

166. **Circularly Polarised Designs.**—Any ordinary selenite design, such as a star or a chameleon, will exhibit these phenomena when followed by a quarter-wave plate properly arranged. But in selenite it is difficult to get films thin enough to exhibit the lower orders of colours, which are most vivid; and hence the most brilliant phenomena are obtained from mica designs, prepared as already described. Mosaics such as Mr. Fox executed are practically the same in effect as a selenite star, prepared of separate fitted pieces in the same way; but by starting from the lowest good colour, and adding thin films, we secure all the most vivid tints and a pleasing gradation. Such single designs are easily prepared after any such patterns as are shown in Plate V.; and after the successive pattern-films are cemented and the balsam is tolerably dry, a

quarter-wave film in its proper position is superposed with fresh balsam, at the same time as the cover-glass is applied. The magnificence of some of these low-order thin-film colours, whilst in transition by the rotation of the analyser, can hardly be imagined until it is seen.

If such a circularly-polarised design be placed in the stage with the quarter-wave film *first*, it behaves precisely like an ordinary selenite or mica, because the polarised vibrations pass through this film quite unaffected. If however, while the analyser is crossed or parallel, the *polariser* be rotated, the rotational colours appear precisely as if the film came last and the analyser were rotated.

In seeking beautiful screen demonstrations of these phenomena, I found the most magnificent effects of all—no other adjective adequately describes them—from superposing in the stage *two* geometrical mica designs, each circularly polarised. The two may either be identical, or different from each other though designed in relation. In this case the rotational colours produced by the first design are again resolved, re-compounded, and circularly polarised by the second design ; and the result is a magical "play" of colour in beautiful kaleidoscopic patterns, which I have never seen equalled, and which is apparently inscrutable until the mechanism is analysed. Even this does not exhaust the variation ; for if when the analyser has been completely rotated (which should be done very slowly, in order that each change in tint may be appreciated) the original polarising plane be rotated a few degrees, the relations of all the film-axes are so altered, that the series of colour variations becomes different ; and so on yet again, until when the polariser stands in an azimuth of 45° the first of the two designs (one of its axes being in the same plane) becomes altogether obliterated, and only the second *single* design stands in colours upon the screen.

These compound mica preparations have given so much delight wherever seen, that I add some details, and in Plate V.

some patterns which I have used, to show the principle and method of combination. The designs lettered A, B, C, are all planned in combination. Both A and B are effective when two similar ones are superposed (of course with their hexagonal points in intermediate positions), in that case making rosettes of twelve points. Any two of the series may also be used in combination; and when either A or C is thus used superposed upon B, each has *two* positions, yielding totally different patterns.

The construction is easy and simple. The basis of each design is a film about $\frac{5}{8}$ wave thick, covering the entire circle. Then for A (Plate V.), a triangular film A B C about $\frac{3}{8}$ wave thick is laid down, and upon this a similar inverted triangle D E F, the other smaller triangles superposing in the same way; all the films being of course so cut that the axis of the mica has the same direction when they are superposed. Finally the quarter-wave film and the top glass covers all. Fig. B is constructed by laying down two circles edge to edge vertically; then two others edge to edge at an angle of 60°; then the third pair at the other angle of 60°, and finally one in the centre. Design C looks complicated, but is easy when analysed. On the base-film is first laid down a film cut as Fig. 184, then a similar shape inverted; then a couple of triangles like the largest in design A; and finally the central six-pointed star.

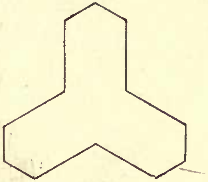


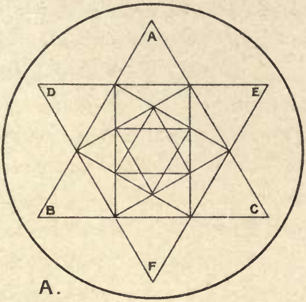
FIG. 184.

At D E F are shown a similar set of octagonal designs. Of this set only D is suitable for duplicating; this makes the most beautiful "rosette" of all. In that figure each successive smaller shape for superposition is readily traced; and E also needs no remark. The design at F can be built up either by superposing four films like A B C D, or four like A B C E; the effect will be precisely the same, if the mica axes are properly kept, but A B C D is easiest, since the points of two films coincide at A C. The design F superposed upon D has two positions, giving totally different patterns.

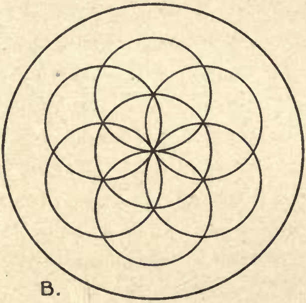
Care should be taken to lay down all "combination" preparations truly centred on the glass. When finished, their combination should be studied, holding a pair in hand. The first or bottom one should be in the usual colour-film position, or most effective position used singly. The other will first be tried in the same position over it, when it may be satisfactory, or not. If not, it should be turned round, one-twelfth or one-sixteenth of a revolution at a time according to the number of "points" in the design, and the effect observed, till this has been seen in every azimuth possible to the combination. Sometimes a pair whose effect is only moderate when one is used as the bottom design, becomes far finer when upper and lower exchange places. When the best result is ascertained, the bottom preparation may be fixed with red putty in a rather thick wooden frame, while the other is dropped loosely into the frame over it so as to be movable, and kept there by a spring wire ring; a little cross or other mark being scratched at the two points (for the *two* pattern positions usually possible) which, when brought to the top of the vertical diameter, give the finest effects. Both designs will of course be so superposed and placed that their covering quarter-wave films stand *next the analyser*.

167. **Waves of Colour.**—But we have not nearly exhausted the beautiful phenomena of rotary polarisation. If the film which we are circularly polarising is regularly graded in thickness, it is obvious that as the colour at any one particular thickness (*a*) passes into the next tint, a slightly greater or less thickness (*b*) next to it (depending on the direction of the rotation) will pass into the former colour of (*a*). And the whole effect will be as if a "wave of colour" had passed across the whole gradation of the thicknesses. We place in the stage the Fox 24-film wedge, and superpose our quarter-wave: on rotating the analyser, a beautiful wave of colour

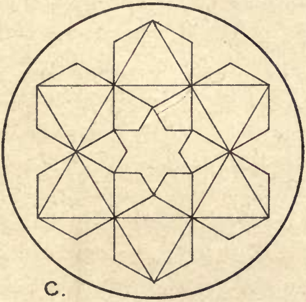
MICA DESIGNS



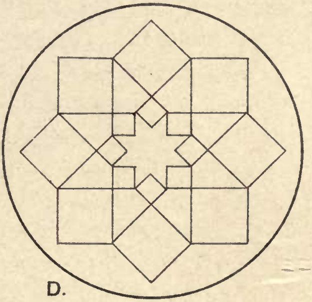
A.



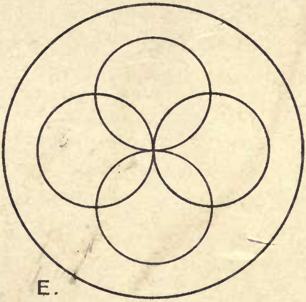
B.



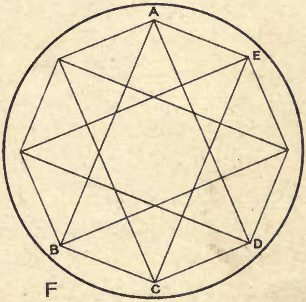
C.



D.



E.



F

A. B. C. *Interchangeable Hexagonal Designs*
D. E. F. *Interchangeable Octagonal ditto.*

sweeps along from end to end. Still more beautiful is it to place a concave selenite in the stage and circularly polarise it: the rings now contract or expand, from or to the centre. The effect of the position of the axes in determining the direction of the rotation, is shown by crossing the analyser, and, keeping that stationary, *rotating the quarter-wave plate:* the rings will then alternately expand and contract, for obvious reasons.

One of the most beautiful demonstrations of these waves of colour is shown in Fig. 185, and may be called a "circular wedge" of mica-films. The usual $\frac{5}{8}$-wave film is the foundation, on which should be plainly scratched a vertical diameter. The other films are best about $\frac{1}{6}$ wave in thickness, and are formed by cutting away from semicircles of mica (arranged with the diameter vertical) angular segments successively increased by 15°, as shown in Fig. 185 by the successive figures 1, 2, 3, &c. The segments thus cut off, it will be readily seen, suffice for another similar (but reverse) preparation. This is an exceedingly difficult design to execute—the most difficult of all perhaps—as there are twenty-two thin films to lay down, and the eleven in each semicircle have to be superposed with one edge and the centres of all the radii coincident. Thin balsam must be used, and the whole should be left rather long to dry before covering. But the effect is beautiful when finished, the radial rosette, when circularly polarised, showing an apparent sweep of colour all round the circle. It is also a beautiful preparation to cross upon a concave selenite or the concentric mica shown in Fig. 173; and the combination may also be circularly polarised.

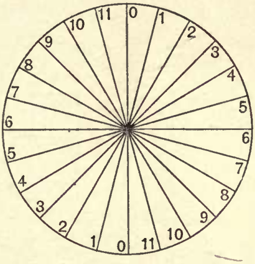


FIG. 185.—Circular-Wedge.

168. **Contrary Rotations.**—There are yet more striking demonstrations. The direction of rotation depends upon the relation of the positive and negative axes in the two films, as

we may show by observing the order of rotation when the quarter-wave is in one position, and then re-adjusting it in a position at right angles therewith: the order will now be reversed. If the plate instead be rotated 90° we have the same effect; and this gives us a very beautiful modification of the experiment, which places the matter in a more striking light. From a plate of mica or selenite, which gives good colours, cut a square about one inch in each side, whose sides shall be perpendicular (as in Fig. 186) when the axes of polarisation are at 45° (the position of most brilliant colour). Cut it in two vertically by the line A B. A moment's inspection of the position of the polarising axes, as denoted by the dotted diagonals, shows that the *inversion*, either laterally or vertically of one of the halves, is equivalent to rotating these axes 90°. Invert one-half accordingly, and having put the two halves together again in the new position, mount in balsam between glasses. By plane-polarised light alone these changes of position make no difference whatever; the whole plate still gives the same colours, complementary in opposite positions of the analyser. But superpose the quarter-wave film as before. When the analyser is either crossed or parallel the colour is still uniform (complementary in the two positions); but between those positions, as it is rotated, the colours change as before, *but in reverse order*, giving different tints like A B, Fig. 187. If the colour-plate be left intact, and the superposed

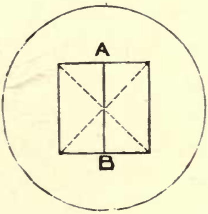


FIG. 186.—Double Mica.

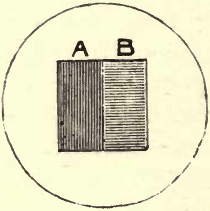


FIG. 187.—Double Mica.

quarter-wave film be in two portions, with their axes at right angles, the effect is exactly the same; but in this case, as the axes are vertical and horizontal, mere inversion is no use, and the two halves of the film must be separately cut, with those axes in proper position.

Such contrary rotations in contiguous portions of a preparation, open up yet another series of exquisitely beautiful colour experiments. The simple demonstration shown in Figs. 186, 187, I have extended by cutting the foundation colour-plate into vertical strips, every alternate one of which is inverted: upon this are superposed quarter-wave films in horizontal strips of the same width, contiguous strips having their axes rectangular. The edge of the whole being blacked out when finished, the effect is that of a chess-board, the adjacent squares of which change tint in reverse orders.

Mr. Fox prepared a superposition quarter-wave in two halves, as at A in Fig. 188, to superpose on his wedge. This gives of course two waves of colour passing along the wedge, one to the right and the other to the left. But I have obtained more striking phenomena by cutting and arranging films as in B C D E of the same figure: B should also be prepared with the lines of division arranged as a St. Andrew's cross. Either C or D (the latter is easily prepared by cutting a single disc into sectors, and "inverting" the four diagonal sectors) may be employed upon a concave selenite, or concentric circles (or in the case of D, it gives still more beautiful effects with concentric squares) of mica, to produce an optical "chromatrope." On rotating the analyser, the concentric bands of colour simultaneously approach and recede from the centre in adjacent sectors; and

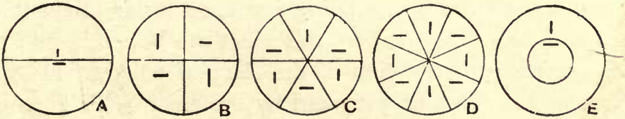


FIG. 188.—Quarter-wave Preparations.

if underneath the foundation pattern a large even colour-film be inserted in a rotating frame, on rotating this the foundation bands themselves are varied in colour (as in Chap. XII.), whilst the contrary adjacent rotations still proceed. Again, any of the designs A B C in Plate V. may be laid down on such a preparation as C, or D in the plate upon D in Fig. 188, with another single quarter-wave on the top of all as usual. Then if the *analyser* is rotated the usual rotational colours only will appear; but when the analyser is crossed, if the *polariser* is rotated, the contrary contiguous rotations of C or D (Fig. 188), will appear. The double circle E is chiefly for superposing upon the circular wedge shown in Fig. 185, when a "wave of colour" will sweep round the circumference in one direction, and round the central portion in the opposite one. But if either of the sector preparations in Fig. 188 be employed as a foundation, with axes in the depolarising or 45° position, and E be superposed, the contiguous sectional areas will be black and white in contrast; and whatever position be given to the second film by a rotating frame, on turning the analyser to a corresponding position, this effect can be produced; thus demonstrating the rotation of the plane of polarisation by two quarter-wave films, as proposed by Professor S. P. Thompson and described on p. 256.

The most remarkable demonstration of the varying effects of films adjusted in different positions, is afforded by the crossed double-wedge shown in Fig. G, Plate IV., so crossed as to give the black diagonals: it was in fact first designed for this purpose. By merely plane-polarised light the figure appears symmetrical; but it is not really so, the effective net difference-thickness having in portions the axis in one position, and in other portions the axis at right angles to this. If therefore we superpose a single quarter-wave, on rotating the analyser the two halves divided by a horizontal or vertical centre-line approach to or recede from each other. On superposing A in Fig. 188 the whole colour-pattern appears to move across the preparation, upwards or downwards. On superposing B the four quarters appear to move rectangularly, giving a sort of rotary effect. And on superposing a four-sector quarter-wave arranged as a St. Andrew's cross, so that the division-lines lie accurately on the crossed diagonals of black squares, the figure beautifully expands or contracts in relation to the centre-lines of those diagonals. These changes are very instructive.

169. **Effect of Polarising and Analysing Circularly.**—We know that if we rotate a colour-film between the polariser and analyser, when its planes are at 45°, it exhibits its colours; but when the planes correspond with those of polariser and analyser, there is no colour, for reasons already explained. But now place first in the stage a quarter-wave plate with its planes at 45°, producing circularly-polarised light; insert in the stage also a *second* quarter-wave plate with its planes at right angles to that of the first;[1] and between them, or after the first plate and before the second, the double mica-film (Fig. 186), in a rotating frame. The circularly-polarised ray from the first plate, after being doubly-refracted by the film, is then again converted into a circularly-polarised ray. It has, therefore, lost all trace of plane polarity; and so when the analyser is crossed, the double film can now be rotated *without the colours changing or differentiating themselves in the least.* The uniform colour will be preserved in all positions. If again brought to the unusual position just indicated, and the *analyser* is then rotated, we get the differential and rotational colours already described.

170. **Spectrum of Rotational Colours.**—Spectrum analysis, as usual, yields us a final demonstration of the nature of these phenomena. We only have to place in the slide-stage a slit, along with the preparation we desire to analyse, and throw the focused rays from the analyser through a

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[1] Or a convenient plan is to have the second smaller quarter-wave plate fitted in the crystal stage described further on (Fig. 181).

prism as usual. Taking a plain film circularly polarised, on rotating the analyser the bands extinguished by interference will travel along the spectrum. With Fox's wedge similarly treated, the whole series of fringes will pass along in the same way. Using a colour-film showing contrary rotations, the slit crossing both halves, the bands will be seen to traverse the spectrum in reverse directions. Using as analyser a double-image prism, and bringing the two images of the slit into line and overlapping each other, the bands in one image will always appear complementary to those in the other.

171. **Phenomena of Quartz.**—Hitherto we have used artificial arrangements for producing rotation; but there are many substances which cause the same phenomena naturally. We have seen that if we place in the slide-stage of the polariscope a plate of calcite cut perpendicularly to the optic axis, so that a beam of parallel plane-polarised light traverses it in the direction of that axis, there is no double refraction, but the plate behaves like a piece of annealed glass. But if we place in the same position a plate of quartz similarly cut, the effects are very different, though quartz also is a uni-axial crystal. The plate shows a beautiful *colour* all over; uniform colour if the light is nearly parallel and the plate truly cut; and as the analyser is rotated the colour passes in succession through more or less of the colours of the spectrum, never becoming white or black, precisely as in the experiments we have been making with mica-films. If we employ homogeneous light, as, for instance, a pure red, and adjust the analyser at 90° so as to give a perfectly dark field, on inserting the plate of quartz we find more or less of the light is restored; but on turning the analyser through a greater or less angle according to the thickness, the light is again cut off. It is, as before, as if the plane of polarisation from the polariser had been *rotated* in one direction or the other, the rotation being greater and greater as we proceed from red to the more refrangible rays. The following is the amount of rotation

produced by plates of quartz of two standard thicknesses in differently-coloured rays :—

Rotation for	1 millimetre	7·5 millimetres
Red	18°	135°
Orange	21½°	161¼
Yellow	24°	180
Green	29°	217½
Blue	31°	232½
Deep Blue	36°	270
Violet	42°	315

With an aperture in the slide-stage over the quartz-plate, and the double-image prism as the analyser, the two discs will always present complementary colours, making white wherever they overlap. Such series of colours are of great value in studying the effects of colour-mixtures.

Fresnel very soon came to the conclusion that the ray of plane-polarised light, on entering the quartz-plate parallel with its axis, was divided into two rays moving in contrary circular orbits, such as we have been studying, of which one was more retarded than the other. By marvellously ingenious reasoning, he concluded that if this were really the case, he ought to obtain each ray separately by a compound prism, as in Fig. 189, where C is a prism of, say, right-hand quartz, and A and B half-prisms of the other, all cut so that the ray traverses them in the direction of the optic axis. He found that he did get two rays, R^1 and R^2, in this way, which showed no variation in brightness as the analyser was rotated, and yet which differed from common light in giving colour when passed through a film of mica or selenite before reaching the analyser. In fact, each ray was found to be circularly polarised, in the same way

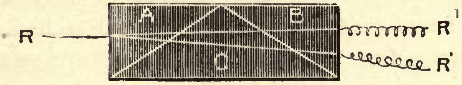

FIG. 189.—Fresnel's Quartz Prism.

as a ray which has passed through a quarter-wave film with its axes at angles of 45° with the polariser. This being ascertained, all the phenomena were easily explained, by the same analysis which we have found it more simple to work out with two successive mica-films.

172. **Right- and Left-handed Quartz.**—It was soon observed that some crystals required the analyser to be rotated to the *right*, and others to the *left*, to produce a given succession of colours; and Sir John Herschel found that this quality of right- or left-handedness was connected with the "set" or direction of certain little facets often found on the shoulders of the crystals. This observation clearly showed another connection between the optical properties of the crystals and their molecular constitution. In the forms of quartz-crystals called *amethyst* or "crossed" quartz, right- and left-handed segments mingle and adjoin in the same crystal. In amethyst the two kinds are mingled in narrow tangential bands, arranged in more or less radial segments, and the contrary rotations in these makes a large plate of amethyst a most gorgeous object upon the screen.[1]

173. **Quartz in Circularly-Polarised Light.**—Conversely to these phenomena, if the quartz be placed in the optical stage, and the quarter-wave plate introduced between it and the analyser (in this case in its normal position, as the plane of polarisation to which it is related is that of the polariser), this will be found to behave nearly like a film of mica, giving in the main two complementary colours and scarcely any intermediate colours. The slight qualification is necessary, because of the fact that all the colours, as we

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[1] Plates of amethyst about $\frac{3}{4}$ inch square can always be obtained; but large crystals are rare. Their beauty depends much upon accurate transverse cutting. A clear *purple* crystal of apparent quartz is always worth cutting, being almost invariably either an amethyst or a "crossed" crystal. In the latter the narrow amethyst bands are absent, but beautiful bands of the contrary rotations are found, radial to the axis as a rule.

have before seen, cannot be *quite* circularly polarised by a plate of mica.

174. **Use of a Bi-quartz.**—If two quartzes of opposite rotations and of equal thickness be superposed in perfectly parallel plane-polarised rays,[1] they exactly counteract each other; and if unequal, the thinner one subtracts from the rotation of the other. As in addition to this the two halves of a "bi-quartz" must show the same colours in two positions of the analyser, while on the least rotation from these positions the colour of each half changes in opposite directions, like the mica preparations described in § 168, a bi-quartz is a sensitive test of any *additional* rotatory power added to either half. When both halves show the same colour, the addition of the merest film of either "right" or "left" makes at once a marked difference.

It is of some consequence to determine what is the thickness of a bi-quartz plate which gives the most sensitiveness to small amounts of rotation. The most common thickness is 3·75 mm., which gives the yellow rays (D line) a rotation of 90°, and consequently gives the purple tint of passage with analyser parallel. Prof. S. P. Thompson has demonstrated by experiment that a more sensitive thickness is double this, or 7½ mm., which rotates the yellow 180°, and consequently gives the tint of passage between Newton's first and second orders with crossed analyser, or on the dark field. A very minute difference differentiates it to blue on one side and red on the other.

175. **Rotation in Liquids.—The Saccharometer.**—Many liquids, and amongst these *sugar syrup*, have the same rotatory power very strongly. As the degree of rotation is found to be strictly proportional to the amount of sugar, &c., in solution, as well as to the length of the column, we have here a most valuable means of ascertaining the strength of the syrup.

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[1] The phenomena of convergent rays are described in the next chapter.

Various arrangements are in use, some more sensitive than others;[1] but nearly all depend on ascertaining either the degree of rotation, or the thickness of quartz, necessary to balance the difference of colour or other phenomena caused by a column of solution of a standard length. This length is very much greater than the thickness of quartz necessary to produce a given rotation; hence it is usual to employ tubes with plane glass ends, from 6 to 24 inches in length. For mere experimental demonstration, a brass or glass tube 2 inches diameter and 3 to 6 inches long, may be capped with glass at each end, and filled with saturated sugar syrup. The front and objective being unscrewed from the polariscope, and moved sufficiently forward, the bi-quartz may be placed in the stage, focused, and its two colours equalised. If the tube with the sugar be then introduced between the polariser and the quartz, so that the polarised beam has to traverse it, it will be seen that the colour of the two halves of the quartz plate is at once differentiated, and that the analyser has to be perceptibly rotated to bring them both alike again. Using a graduated glass circle with the bi-quartz, and connecting a pointer with the front of

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[1] In Mitscherlich's instrument, the amount of rotation needed to restore a simple dark field after the column of fluid is introduced, is observed by the light of a sodium-flame. In Soliel's a bi-quartz is used. In Wild's a doublequartz-plate showing "Savart's bands" (see § 201) is employed, the bands being first extinguished, and the angular rotation necessary to restore extinction being observed. In Jellett's instrument a peculiar calc-spar prism is the analyser, which gives two images polarised in two planes very slightly inclined, and which are brought to equal brightness: then the rotatory substance differentiates them. Cornu employs in the same way, but as polariser, a Nicol cut longitudinally in two, which halves are very slightly inclined to each other. Laurent covers half the field with a half-wave plate. The principal forms of chemical polariscopes are described and figured in Dr. Landoldt's *Handbook of the Polariscope and its Practical Applications* (Macmillan & Co.); but I do not think Jellett's form of double-prism (for description of which see *Transactions of the Royal Irish Academy*, vol. xxv.) has nearly had justice done to it in comparison with others; in fact it has often struck me that Germans rarely do justice to English physicists or inventors.

the polariser (which may of course be rotated instead of the analyser), the amount of rotation will be shown on the screen; and it can also be shown that it is only half as much with a syrup of half the strength. Without a graduated plate, it can be shown that a column 6 inches long gives the same rotation as a column of 3 inches of syrup containing twice the quantity of sugar in the same amount of water.

Spirits of turpentine give the same phenomena, and oil of lemons in a still more marked degree. By using a more sensitive bi-quartz, in which each half is composed of superposed *wedges* of right- and left-handed, or of slices cut in other directions and put together in particular ways, displacement of the colours may be shown on the screen by a cell containing only 1 inch of fluid, which will go with the quartz into the optical stage. One of the best forms is that shown in Fig. 190, where A is a wedge, say, of right-handed, and B of left-handed quartz in the half A B, whereas in the other half C is left-handed and D right-handed. Across the middle, where all four wedges are of equal thickness, there is, of course, a black line when the analyser is crossed, and white when it is parallel with the polariser, the right and left quartzes there neutralising each other. On each side of this there are necessarily coloured straight bands, as shown, exactly similar in two positions of the analyser; but as in one half the right-handed quartz is thickest in all below the middle line, and in the other half the left-handed quartz, any rotation of the analyser, or introduction of fluid or other substance possessing any rotatory power, displaces all the bands in opposite directions. A very slight addition in rotatory power is thus perceptible.

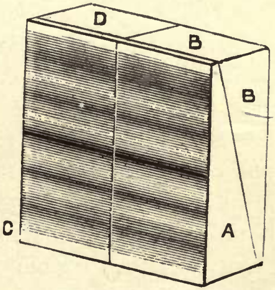

FIG. 190.—Compound Wedge Bi-quartz.

The variety of effect possible from various wedges or sections of quartz in combination, or rotated, is in fact almost endless; but it may be mentioned that a large concave plate cut across the axis gives, of course, Newton's rings, whose colours change, the rings moving inwards or outwards as the analyser is rotated, as in a concave selenite circularly polarised (§ 167). Lastly, a large quartz plate is exceedingly good as a "superposition" plate, as the colour may be changed by rotation of the analyser till the most pleasing effect is produced.[1]

176. **Other Rotatory Crystals.**—Many other crystals besides quartz have the power of rotating a polarised beam. Amongst these may be mentioned cinnabar, periodate of soda, sulphate of strychnia; and there are others. Chloride of sodium (common salt) has sometimes the property *in all directions*, therein resembling liquids.

177. **Electro-magnetic Rotation.**—Faraday discovered that a cylinder of glass placed axially between the poles of a powerful magnet, or surrounded by a helix traversed by an electric current, similarly rotated the plane of polarisation, differentiating the two colours of a bi-quartz. His "heavy" glass (borate of lead), and some peculiar forms of flint-glass, give the most effect; good ordinary flint having a rotatory power about half that of the "heavy" glass. Further experiments have shown that the electro-magnetic current rotates the beam in *some* degree through nearly all, if not all, liquids, and even gases, thus opening up many most interesting questions of molecular physics.

Dr. Kerr further discovered that a beam of plane-polarised light reflected from the polished pole of an electro-magnet, also showed rotation whenever the iron was magnetised by the passage of a current. It has also been found that light is rotated when passed through a film of iron thin enough to be transparent, when the film is normally magnetised by a current, or when the magnetic poles lie in the direction of the ray.

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[1] Since the first edition of this work was published, what is known as Klein's quartz plate is generally fitted to petrological microscopes.

But there is this remarkable difference between electro-magnetic rotation and other forms of the same phenomenon. If we reverse a quartz, the ray is still rotated in the same direction. Consequently, if we reflect the ray back again through the same quartz, the rotation conferred by the first transmission, is exactly reversed by the second : the circular waves *go back* upon their former paths. In glass or fluid whose rotatory property depends upon electro-magnetic action, on the contrary, the rotation is repeated in the reflected ray; and whichever way the ray is transmitted, and as often as it is transmitted, it follows the direction of the current.

178. **Optical Torque.**—In all these ways the rays of polarised light appear to be, as it were, *twisted* on the axis or line of propagation, or subjected to a torsional force; and Prof. S. P. Thompson[1] has suggested for this effect the term, borrowed from mechanical technology, of "optical torque." For a more obvious measure of this torque or twist than the revolution of the analyser which we have employed,[2] he has further devised the ingenious mica preparation shown in Fig. 191. This is constructed of twenty-four sectors of 15° each, laid down edge to edge, and all so cut from the same sheet, that the polarising axis of each is radial. This is easiest done (at least in my hands: I do not know Prof. Thompson's exact method) by cutting a horizontal band of mica as wide as the radius, with the mica-axis vertical or across the band, and then cutting off successive narrow triangles by cuts at an angle of $7\frac{1}{2}$° with the vertical: each triangle will have its apex the opposite way to its predecessor, but this in no way affects the axes when all are put together. The most effective thickness is obviously a half-wave, as this gives a bright field in the four sectors standing in azimuths of 45°, while the vertical and horizontal sectors must give a black cross: hence we thus get

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[1] *Proc. R. S.*, May 17, 1889.

[2] That is, more spectacularly obvious. It is not really so sensitive as other methods.

the most contrast. If now a quartz plate be introduced, or anything else which by any of the preceding methods exhibits torque or rotation, the cross shifts round conspicuously. Of course the cross is no longer black: a little thought will show that a quartz 3·75 mm. thick, rotating the yellow 90°, must

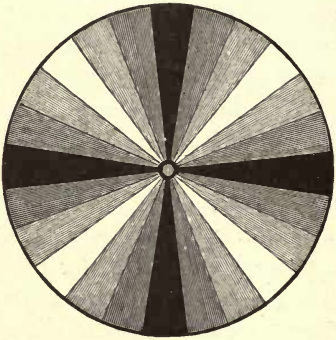

FIG. 191.—Thompson's Rotation Register.

produce a yellow one, while 7·5 mm. will bring it back to the "tint of passage;" but the twist upon the screen is as visible as if it were so.

A large rosette crystal, such as one of salicine, may be used in the same way; or so may be the crystalline lens of a fish; or a circular disc of chilled glass.

179. **Rotation or Torque of Common Light.**—The remarkable fact has lately been proved, that this optical torque affects not only polarised, *but also common light.* This has been demonstrated by help of the interference fringes produced by Fresnel's bi-prism (§ 111). This experiment being arranged as usual to show the fringes on a screen, Prof. Abbe superposes upon the bi-prism a bi-quartz 1·88 mm. thick, its line of demarcation coinciding with the angle of the bi-prism. From the table on p. 319 it will be seen that this thickness rotates yellow rays 45°, and as this is done in each direction,

the result is that the two beams are twisted into positions at right angles to each other. We know already, that with polarised light rays thus treated cannot interfere; but it proves to be *the same with common light*, and consequently the fringes vanish from the screen.

Prof. Sohncke has shown that the same twist of the rays of common light is produced in heavy glass by the electro-magnetic current.

180. **Reusch's Artificial Quartz.**—The general resemblance of the phenomena produced by plates of quartz traversed in the direction of the optic axis by parallel plane-polarised light, to the phenomena of mica-combinations, has clearly appeared in foregoing experiments. The resemblance is however so far not quite complete, the succession of colours with two films being not quite so perfect and gradual as with a quartz of sufficient thickness. But it occurred to Prof. Reusch, who was acquainted with the artificial uni-axial crystals composed of crossed mica-films described in the next chapter, and discovered by Nörrenberg, his predecessor at the University of Tübingen, that by superposing thin films of mica with their similar polarising planes successively twisted at regular angles round an axis, the phenomena of quartz should be *perfectly* reproduced. His method is shown in Figs. 192 and 193, which represent arrangements for a right- and left-handed combination. The three rectangular slips numbered 1, 2, 3, in each figure are so cut that the principal polarising plane is parallel to their longest sides. They are then superposed in the order of the numerals, each slip at an angle of 60° with the one underneath; and in this way a tolerably large number of films (which must be a multiple of six—say eighteen to thirty-six $\frac{1}{8}$ wave thick), are built up, and cemented together with balsam and benzol. Such combinations will give a perfect rotation of colours in the direction of the numbers, right or left. Instead of an angle of 60°, we may adopt that of 45°, or half a right angle; in which case it will require eight

films to complete each circle, and the total number superposed should be a multiple of eight.

These artificial quartzes offer a beautiful proof of the theory of Fresnel respecting the two contrary circular waves. Mere inspection of Fig. 192 will show how one of the polarising planes, *a b*, is successively changed in direction; making several revolutions while the ray gets through the total combination. And detailed analysis of the "resolution" of the rectangular vibrations by each successive film, and finally by the analyser, will show that the total result is equal to that of the two contrary circular waves we have been studying in detail. Fresnel's theory was thus verified, years after the author had been removed from the scene of his brilliant discoveries. These combinations moreover give, perfectly, *all* the phenomena of quartz as further described in the next chapter (§§ 188, 200).

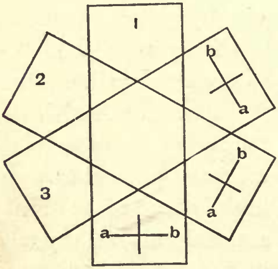

FIG. 192.—Mica Quartz.

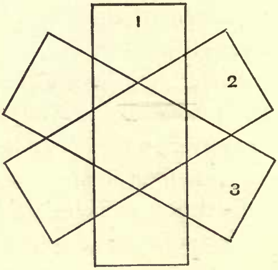

FIG. 193.—Mica Quartz.
Reversed Rotation.

Professor Reusch's films were actually built up, as above described, of oblong slips; but such is not the easiest way of making them in practice. The long slips consume so much mica, that it is difficult to get all the films exactly equal, which is essential. But the object can be easily obtained by another method of construction, adopted by Mr. C. J. Fox in making the finest preparations of the kind which have ever come under my notice. A large film of mica being procured, from which all the films for the same preparation are to be cut, scratch the whole sheet out into squares at the proper angles. For instance, supposing the preparation is to be built up of films superposed at 45°, half the sheet will be covered by squares like Fig. 194, with sides parallel to the polarising planes, and half by squares at an angle of 45° with them, as Fig. 195. These may then be cut up with the knife and rule, but, before doing so, scratch some mark in one given corner of every square, by which the position of that corner can be distinguished. Then if we take first a square from Fig. 194, and superpose on it a square from Fig. 195, *turned round* 45° (say to the left), so as to coincide; next another from Fig. 194, *turned round* 90° *to the left;* and next a second from Fig. 195, turned round 90° to the left; we shall have gone accurately round half the circle, and the whole preparation can be built up in this manner. If 60° be the angle adopted, equilateral triangles may be successively rotated, and the alternate triangles with apex inverted may be used for a preparation of contrary rotation. The best effects are obtained with not less than about twenty-four films, as nearly $\frac{1}{8}$ wave thick as possible; but Mr. Fox made fine preparations consisting of as many as forty-two films; and on the other hand, moderately good results may be got from as few as a dozen films a quarter-wave thick, arranged in four ternary sets. The main thing is absolute uniformity in thickness, which can only be obtained by using the same sheet for all the successive films.

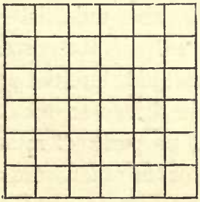
FIG. 194.—Mica Squares.

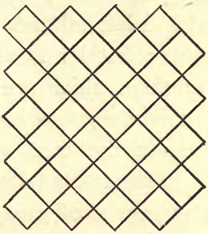
FIG. 195.—Mica Squares.

181. **Rotation and Molecular Constitution.**—It is not difficult to conceive of twist or torque as produced by the electro-magnetic current. Remembering what we have found regarding the consequences of electric stress in liquids, and the proof thus given that electric stress is ultimately a stress in the ether, it is natural to imagine that a rotary current should produce rotation in the particles of ether. The peculiar behaviour in regard to direction of twist of electro-magnetic torque (§ 177) seems most consonant with this supposition. But when we consider the rotatory power of various natural bodies, we stand on the threshold of molecular questions of absorbing interest.

We have seen that a limited number of crystals possess rotatory power. Nearly all of them are found both right-handed and left-handed. They are all either uni-axial or have no double-refraction at all. And, as a rule, if not universally,[1] those of them which are soluble in any fluid, lose the property of rotation when so dissolved. We are driven to the conclusion, that in the case of crystals the property of rotation is dependent upon crystalline structure; or, in other words, upon the arrangement of *groups* of molecules. This supposition is confirmed by the fact that in most of such substances the ray of light must pass through them in one particular direction—that of the single optic axis—to be rotated. And it is still more strongly confirmed by the successful reproduction of the phenomena by twisted mica-combinations as just described (§ 180).

We might suppose the same of liquids—that is, that the property depended upon the arrangement of molecular *groups*—were rotation confined to the liquid state. But experiment proves that when rotatory liquids are volatilised, the *vapour* exerts sensibly the same rotatory power, for equal weights, as the liquid. We are, therefore, forced to the conclusion that in this case the property depends upon the *single* molecules of which the gaseous

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[1] I am not sure that the rule is quite universal.

matter is composed. As analogy compels us still to regard it as dependent upon some twisted "structure," we are driven to the further deduction that here rotation depends upon the *grouping of atoms into the molecule.* It has, indeed, been disputed whether in liquids there really is actual circular double-refraction, as in quartz, whose two circular waves were so triumphantly separated by Fresnel; and Dove's experiments failed to decide the matter.[1] But the primary phenomena which led Fresnel to *suppose* it in quartz exist in the case of liquids; he himself, in a paper presented to the French Academy on March 30, 1818, reports experiments which he held to bear out this view; and my own experiments in the production of spiral figures (see Chapter XIV.), in which quartz is successfully replaced by either rotatory fluids or mica-combinations, are very strong evidence in favour of the existence of similar circular waves.

Regarding the molecule, then, as the source of the property, it is strangely significant to find that all the substances possessing rotatory power in solution or vapour, are *complex carbon compounds.* Beautiful and refined researches by Pasteur, Le Bel, Van't Hoff, and others, have moreover shown that in all such substances there are one or more *asymmetrical* carbon-atoms; but, on the other hand, there are carbon compounds which contain such asymmetrical atoms in which no rotation has yet been observed. Very early in the history of this research, however, a tartaric acid with no rotation was separated into two varieties of *opposite rotations*, whose combination makes the neutral form. These two forms of rotatory tartaric acid, though in most reactions and in chemical constitution identical, differ in some reactions, and crystallise in right-handed and left-handed forms (§ 172). There were a few other substances in which the inactive and one rotational form, but not the other, were known; and some—especially several ethereal oils—in which opposite rotations, but not the neutral

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[1] Poggendorf's *Annalen*, cx. 290.

form, were known. Some of these few forms with different optical properties, as known ten years ago, had been obtained with great difficulty; and hence the theory was advanced, that all carbon compounds containing asymmetrical atoms really are composed of molecules whose atoms may be arranged helically, but that in the inactive ones two or four such molecules of opposite rotations were combined in a kind of sexual combination, and had not yet been separated.[1]

This reasoning was reinforced by the consideration, that substances which possess rotatory power in fluid or solution, when capable of crystallisation, crystallise almost, if not quite, invariably as *bi-axials* (see Chapter XIV.), which itself is a strong evidence (see § 192) of unsymmetrical atomic structure. In crystallising they appear to lose their rotatory power; but as this would be, with our present means of observation, overpowered (in any direction of the ray) by the far stronger *ordinary* double refraction, this can hardly be held to be proved. If the crystals are melted, however, so as to destroy the crystalline structure and restore the amorphous condition of a fluid—as, if a crystal of sugar be fused—the rotatory property is restored (or remains). Heat also converts some rotatory substances into inactive forms; as if there were a

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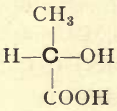
[1] By an *asymmetrical* carbon-atom is meant, in chemical language, one united to four *different* groups, carbon being tetravalent. Thus in lactic acid, the carbon-atom is united as in the diagram to the four other atoms or groups. Now let the carbon-atom **C** be conceived as occupying in space the centre of a tetrahedron, and the four other groups, the four angles thereof. Draw two such tetrahedra as standing upon a horizontal surface, and let the same atom or group—say CH_3—occupy the apex of each. Then in every asymmetric case, as above, it will be found that the other three groups may be arranged round the angles at the bases, so that one tetrahedron may be, as it were, the image of the other in a mirror, and its three groups range round the base in reverse order to the other. This is believed to represent the two opposite rotations of lactic acid. More complex cases are similarly explained.



$$\begin{array}{c} CH_3 \\ | \\ H—\mathbf{C}—OH \\ | \\ COOH \end{array}$$

Lactic Acid.

tendency under the influence of heat vibrations for a number of molecules to pass into the form of the opposite *sex*, as it were; the two kinds afterwards uniting in pairs. The strong tendency of quartz to combine molecules of opposite rotation in the narrow bands of the amethyst, has already been noticed (§ 172).

Such was the position of the question when the first edition of this work was published; and the whole course of scientific discovery in the department of organic chemistry ever since, has been an eloquent testimony to the value of this clue towards the nature of atomic grouping into the structure of molecules. With this clue to guide chemists, scores of isomeric compounds have since been discovered, known as giving both opposite and neutral rotations; and the organic chemist is now to a large extent occupied, under the name of "stereo-chemistry," with the nature of the *actual geometrical grouping of atoms in space* into the molecule, as the only means of explaining the wonderful variations with which he has to deal. Many new compounds useful in medicine or the arts, and many of the recent discoveries of Fischer in the synthesis of the sugars, are directly due to the wonderful insight afforded by the rotation of polarised light, into the very structure of the molecules[1] from whose reactions the new substances have been derived.

182. **Effects of a Revolving Analyser.**—This seems the fittest place to describe briefly the beautiful apparatus devised by Mach,[2] by which not only many of the preceding rotational phenomena, but much else generally made visible

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[1] The most accessible account of the methods and results of stereo-chemistry, up to the date this is written, will be found in Marsh's *Chemistry in Space* (Oxford, 1891), or the article upon "Organic Chemistry" in *The Year-Book of Science for* 1892 (Cassell's).

[2] There is no doubt that the apparatus is due to Mach, who first described it in *Proc. Vienna Academy*, Jan. 4, 1875; and that Mr. Spottiswoode's, described in *Phil. Mag.* xlix. 472, was based upon this description, as was also Duboscq's, produced and described still later.

on the screen in succession by rotation of the analyser, can be shown there at the same moment. The analysing Nicol is mounted, so that either a slit or square aperture can be attached to its first face, in one end of a tube which can be made to revolve swiftly by a multiplying wheel, the outer or screen end of the tube carrying a deviating glass prism, to deflect the beam somewhat from the optic axis of the polariscope. Beyond the prism is a focusing lens. The light from the polariser now traverses any crystal in a stage as usual; but on revolving this analyser, the effect is that what would have been a changing central image, is by persistence of vision and the deviation, spread out into a circular ring, on which *all* the phenomena appear together. The radial deviation is of course arranged in the plane of the analyser, and rotates with the latter.

With this apparatus many beautiful experiments can be performed. If we use only the square aperture, the ring will be bright at two opposite points, and dark at two intermediate points, shading from one into the other. With a selenite in the stage, let us say giving blue and yellow, we shall have blue at two opposite points, yellow at the two intermediate, and no colour at the 45° points, all graduating gently into each other. With a quartz cut transversely in the stage, we have the rotational colours we have been examining, spread round the ring, twice repeated. The ring gives the successive appearances all together.[1]

Mach's apparatus is however further fitted, next beyond the deviating prism, with a direct dispersive prism,[2] whose dispersion is also in the plane of the revolving analyser. When this

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[1] Mr. Spottiswoode substituted for Mach's Nicol and deviating prism, a double-image prism, which gives both the usual central image, and the ring around it. Otherwise his instrument was practically the same.

[2] A simpler plan would be to use one direct prism only, with the refraction only partly corrected. Much loss of light would be saved in this way, with the only drawback that the prism would be of little use for any other apparatus.

is used, a slit instead of the square aperture is attached to the first face of the analyser, and after focusing, is dispersed: the violet end should be towards the centre, in order to equalise the fainter luminosity at that end. If now we place in the stage a thick plate of selenite—say 1½ mm. thick, too thick to exhibit any colours—there will be on revolving the analyser a circular spectrum, violet inside, which will be continuous at all four 45° points of the circle, but crossed by black interference fringes, appearing as concentric arcs, along the horizontal and vertical diameters. The fringes in one diameter will of course be concentric with the bright bands in the diameter at right angles, showing the complementary phenomena. Placing in the stage a quartz plate, with which we have already studied the shifting of the bands along the spectrum as the analyser is rotated, it is manifest that with the revolving dispersion the circular spectrum will be traversed by black fringes, in the form of continuous spirals. This is a screen demonstration of exquisite beauty.

The projection of the rotational colours of circularly-polarised mica-films by the same apparatus, is too obvious to need any further explanation.

CHAPTER XIV

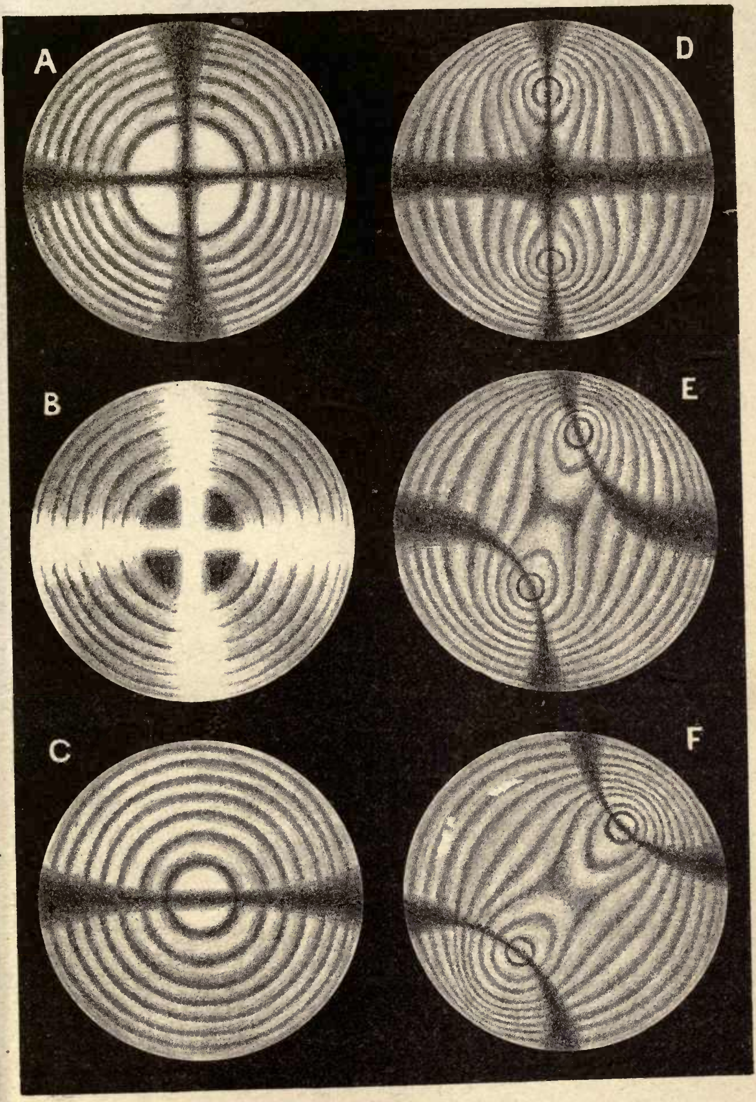
OPTICAL PHENOMENA OF CRYSTALS IN CONVERGENT POLARISED LIGHT

Rings and Brushes in Uni-axial Crystals — Cause of the Black Cross — Apparatus for Projection or Observation—Preparation of Crystals—Artificial Crystals--Anomalous Dispersion in Apophyllite Rings--Quartz—Bi-axial Crystals—Apparatus for Wide-angled Bi-axials—Anomalous Dispersion in Bi-axials--Fresnel's Theory of Bi-axials—Deductions from it—Mitscherlich's Experiment—Conical and Cylindrical Refraction—Relations of the Axes in Uni-axials and Bi-axials—Composite, Irregular, and Hemitrope Crystals—Mica and Selenite Combinations—Crossed Crystals—Nörrenberg's Uni-axial Mica Combinations—Airy's Spirals—Savart's Bands—Crystals in Circularly-polarised Light—Result of Polarising and Analysing Circularly—Quartz in Circularly-polarised Light—Spiral Figures—All the Phenomena due to Interferences of Waves.

183. **Rings and Brushes in Uni-axial Crystals.**—To some extent we have already found proofs of the close connection between the form and other physical characteristics of crystals, and the optical phenomena they present. But since we have found polarised light such a delicate analyser of the inner constitution of bodies, acting as a sure revealer of any state of unequal tension, however caused; of invisible sonorous vibrations; and even of electro-magnetic stress; it is natural to inquire if it will not yield us further evidence of the molecular constitution of the crystals themselves, or the plan

Pl. 6.

RINGS AND BRUSHES IN CRYSTALS.



A. *Calcite, analyser crossed*
B. *,, analyser parallel*
C. *Single Axis of Topaz*
D. *Nitre, showing both axes*
E. *,, slightly rotated*
F. *,, axes rotated 45°*

on which they are, as it were, built up. This line of inquiry takes us into a new and magnificent range of optical phenomena, to enter which we have simply to abandon the nearly *parallel* beam of light we have hitherto employed, bringing to bear upon our crystals pencils of polarised rays distinctly convergent.

Provide a plate of Iceland spar, cut across the axis, and about $\frac{1}{8}$ inch thick. It need not be large; and for the lantern polariscope it may be conveniently mounted between two thin glass circles, in the centre of a wooden slider four inches long by $1\frac{1}{8}$ inches wide (Fig. 196). Placed in the centre of the optical stage, so as to get the *parallel* beam of polarised light we have already discovered (§ 132) that it acts as a mere plate of glass, producing no effect; its image is dark or light, according as the analyser is crossed or parallel. But now imagine *converging* or *diverging* rays, or a conical pencil of plane-polarised rays, such as are produced by a converging lens, passing through the plate. It is evident that only the central rays can pass exactly along the optic axis; and that all inclined rays must be more or less doubly-refracted. At equal distances all round the axis of the pencil, therefore, the plate must act as a thin film, and give colour arranged in symmetrical circles.

FIG. 196.—Calcite Plate in Slider.

But this is not all. We have already learnt the two directions into which the original polarised plane of vibration must be resolved in the crystal, and that one of the two planes must *pass through the axis.* The other of course is at right angles to it (§ 133). Taking therefore Fig. 197 as a diagram of our plate, and supposing A B to be the original plane of vibration from the polariser, the plate of calcite resolves that, everywhere, into vibrations passing through the axis, represented by the radii; and others at right angles to them, represented by tangents. Further still, it is evident that in the planes of the two radii, A B and C D, there will be no double refraction at all, since there the planes of vibration in the crystal coincide with that of the polariser, and that perpendicular to it. Along those lines, therefore, the plate can have no influence, and must appear black when the analyser is crossed, and white when it is parallel with the polariser (§ 149).

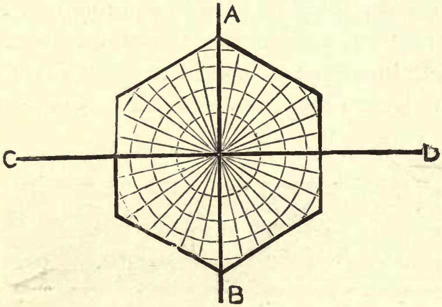


FIG. 197.—Vibration Planes in the Calcite.

All this is so in experiment; but to exhibit it on the screen, we must add to the polariscope what is called a "crystal stage," which will hold the plate in a converging cone of rays from the objective. Fig. 198 shows the construction of it. A tube, A B, fits on the nozzle of the objective, and has transversely cut through it a slit, S, through which the crystal sliders are passed, kept in place by a spiral spring as usual.

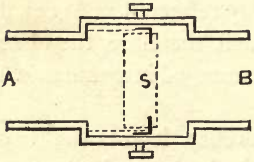


FIG. 198.—Crystal Stage.

The end, B, of the tube is of exactly the same size as the nozzle, so that the Nicol or other analyser fits and rotates in it, as on the nozzle. We place this addition on the nozzle, add the analyser, and insert our plate of calcite in the slit, s. We at once get on the screen the beautiful figures represented at A and B, Plate VI. according as the analyser is crossed, or parallel with the polariser. In the former position the beautiful coloured rings are traversed by the black cross we were led to expect; in the other position, we get the complementary rings traversed by a white cross. The centre, of course, shows no phenomena at all beyond white or black, as the rays there pass along the optic axis.

184. **Apparatus for Observing the Rings.**—The objective described in Fig. 1 gives, in practical work, about the best convergence for average effect with "crystal rings," unless an addition to be presently described is made to the apparatus. Much more convergence, unless the extra lenses are added, causes a great deal of light not to get through the analyser; and much less gives fewer rings, unless a very thick plate be employed. For a moment's consideration will show that the amount of retardation in a plate of crystal thus cut, depends on both the thickness of the plate, and the amount of convergence; and that the rings must become closer and more numerous as the plate increases in thickness, or the light is more converged. The private student will often find a simple tourmaline pincette (Fig. 199) the most convenient apparatus. A slice of tourmaline is mounted so as to be capable of rotation at each end of the spring tongs, and the crystal plate to be examined is held

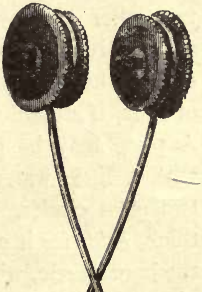


FIG. 199.—Tourmaline Pincette.

between them: the rays passing through this simple polariscope into the small pupil of the eye, are sufficiently convergent to exhibit the phenomena. Or a single loose tourmaline, such as the one used in the rotating frame, held close to the eye, with the crystal close up to it, will show the rings well, if the whole, and the eye, are turned towards the plane-polarised light from a glass plate or any other polarising surface, or even towards certain portions of a bright sky (see Chapter XV.).

185. **Preparation of Crystals.**—Many crystals can only be prepared, as a rule, by skilled workmen; and an immense variety of uni-axials and the bi-axials to be next considered, may be obtained from Messrs. Steeg and Reuter, Homburg vor der Höhe, who prepare this class of objects for almost the whole world. The rarer crystals can hardly, in fact, be obtained elsewhere; but Messrs. Darker, Hofmann of Paris, and one or two other opticians, prepare calcite, quartz, borax, sugar, and some dozen others of those most usually inquired for. Several crystals, however, are within the reach of the amateur. Nitrate of soda, if a good clear crystal can be found, is a fine uni-axial. A plate may be ground on ground glass, polished partially with a little water, and mounted in Canada balsam between two glass circles. Or, in winter a piece of clear *ice*, $\frac{3}{4}$ inch thick, *held* (for it can hardly be placed in the stage) in front of the bare nozzle, with the Nicol held in front and rotated, will give beautiful rings. Ferro-cyanide of potassium (prussiate of potash) is a cheap crystal, found in prisms or tablets, and easily split across the optic axis in slices, which have natural polished faces, and therefore need no other preparation than to be protected in balsam between two glasses. It is normally a uni-axial showing circular rings; its other frequent phenomena will be treated of presently. Hyposulphate of potash is another crystal which gives fair rings, as do phosphates of ammonia or potash. Many of the soft crystals, uni-axial or bi-axial, after grinding on ground glass or stone, only need rubbing once or twice with the wet finger, the balsam in which

they are mounted perfecting the polish, as it is nearly the same index of refraction as most of them. Others can generally be polished with a little putty powder or colcothar on a piece of fine silk. Sugar must be done dry or with a little oil.

186. **Artificial Crystals.**—Dr. Brewster made *artificial* crystals by melting together equal parts of white wax and rosin, thoroughly mixed, and with a pointed rod dropping two or three drops on a small circle of glass, on which was laid a similar circle, forced down on the composition with a strong pressure. The molecules are thus subjected to strong compression in a direction perpendicular to the plates; and the result is not only double refraction, but the slide shows rings like a crystal in convergent light.[1] Mr. H. G. Madan tells me that about a dozen layers of sheet gelatine cemented together with balsam give very fair results, the films shrinking so much in drying as to acquire doubly refractive effects.

187. **Anomalous Dispersion.—Apophyllite Rings.**—From the phenomena of anomalous dispersion (§§ 60, 72) we should expect that some crystals would show exceptional phenomena, similarly due to exceptional retardation of various colours. The fact is so. Apophyllite, for instance, is remarkable for the fact that it is "positive" (§ 135) for one end of the spectrum, "negative" for the other, and non-doubly-refracting for some intermediate colour, generally yellow. Hence we have, instead of rainbow circles as in most cases, rings nearly *white and black:* the usual effect being black rings lined, as it were, with green only. We have here, therefore, a phenomenon of another kind due to "anomalous dispersion." By combining slices of certain positive and negative crystals cut of suitable thicknesses, it would be supposed that this curious phenomenon should be produced artificially. Such is the fact: but each pair of crystals has to be mutually selected,

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[1] It is very easy to get colour in this way, but in the few trials I have made I have never got perfect rings to please me; probably for want of pressure, as I only used that of my hand.

one with reference to the other, else the counter-action is not sufficiently accurate.[1]

Apophyllite also shows in some specimens a most beautiful tesselated or "mosaic" construction. This, however, is more analogous to the compound crystals mentioned further on. Such crystals have to be specially sought for and selected.

188. **Quartz in Convergent Light.**—The phenomena of quartz are what we should expect from those already observed in parallel light. Where the light is distinctly convergent, the ordinary doubly-refracting forces come into play; showing circular rings and a cross. Towards the centre, however, the rotatory power of the nearly parallel axial rays comes more into play; and hence there is never a black centre as in most other crystals, but a coloured area, of a size according to the convergence of the rays, the colours changing with rotation of the analyser. The quartz system is represented in A, B, Plate VIII. As a plate of quartz cut parallel to the axis only produces plane vibrations like those of selenite, Sir George Airy suggested that the normal vibrations in such crystals were *elliptical*, of which the circular and plane waves were extreme limits. This theory, when applied mathematically, is found perfectly to account for all the phenomena, including those of superposed plates presently described (§ 200).

189. **Bi-axial Crystals.**—It has been stated already (§ 136) that there are many crystals in which neither of the two doubly-refracted rays follows the ordinary law, but both are extraordinary; the index of refraction varying with the direction of the ray, and the refracted ray not being always in the plane of incidence. Such crystals, upon careful experiment, are found to contain *two* directions in which a ray is not doubly-refracted, inclined to each other at some angle; and

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[1] Calcite is generally used for one of the pair; but the reader should be specially warned against lead hyposulphate for the other, as often supplied by crystal cutters. The lead salt invariably becomes perfectly opaque in a short time.

each of these optic axes is surrounded by a system of rings. Such are accordingly termed " bi-axial " crystals.

The only bi-axial crystals suitable for the ordinary lantern polariscope are those whose axes are not much inclined to each other, so that both systems of rings can be seen at once. The four best are nitre, native crystals of lead carbonate (cerussite), glauberite, and some varieties of the felspar called adularia. The last must as a rule be purchased; but the only difficulty about nitre is procuring a good crystal to work on. They all look beautiful as they come out of the crystallizing vats; but as they dry, nearly all spoil by decrepitation and striæ, and very few remain clear. A far from perfectly clear one, however, will show very fairly. We want a six-sided prism about $\frac{1}{2}$ inch diameter. Split a slice about a $\frac{1}{4}$ inch or more thick, as truly across as possible, with a knife; and then carefully grind it down on a dry stone till about $\frac{1}{8}$ inch thick, transversely to the axis of the prism. Finish it with a little water, on first a roughish and lastly a smooth ground glass, finally wiping off the moisture with the finger. If necessary give it a lick on each side, and again rub with the finger, which will nearly polish it as already described; then mount it with balsam, or balsam and benzol, between two circles of glass, and finally mount in a wooden slide with some soft cement, that will allow of adjustment rectangularly to the axis of the polariscope. When adjusted with the line joining the optic axes parallel to or across the plane of polarisation, and the analyser crossed, the appearance is as in D, Plate VI.; with the analyser parallel, of course the cross is white and colours complementary. But if with analyser crossed the *crystal* be rotated, the phenomena change beautifully, the cross opening out into hyperbolic curves (E, Plate VI.), which, when the axes of the nitre stand at 45° across the plane of polarisation, assume the shape of F. The shape of these rings (lemniscates) and black brushes can all be mathematically calculated on the principle of interference.

The following is a list of a few good crystals most easily procured, the angles being quoted from various authorities. These are the real angles of the axes in the crystal itself, but the *apparent* angle is much increased by the refraction into air of the oblique rays. The angles vary somewhat, (§ 199), and scarcely two authorities quote the same.

Glauberite	2° to 10°
Lead Carbonate, or Cerussite	8° 7′
Nitre	7° 12′
Arragonite	18° 18′
Titanite	30°
Borax	38° 32′
Mica [1]	45°
Sulphate of Zinc	44° 4′
Topaz	50°
Sugar	50°
Selenite	57° 30′
Nitrate of Silver	62° 16′

190. **Apparatus for Exhibiting or Projecting Wide-angled Bi-axials.**—With the usual moderate convergence of the lantern polariscope, we cannot thus see *both* systems of rings in bi-axials whose axes include great angles; and it is usual to cut such crystals at right angles to one of the axes, when of course we get approximate circles round that axis alone, traversed by *one* arm of the nitre cross, *i.e.* by a straight black brush through the centre. Topaz (C, Plate VI.) is a fine crystal cut in this way; so are borax and sugar.

By some addition to our apparatus, however, it is possible to see at once, or to project, both systems of rings in wide-angled bi-axials. Nörrenberg first invented a system of lenses to accomplish this object, the arrangement mainly consisting of

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[1] Mica differs exceedingly, from a uni-axial up to as much as 75° (see § 199).

two nearly hemispherical lenses about $\frac{1}{2}$ inch diameter, between which the crystal is placed, backed by other lenses still further to converge the light; and with an additional focusing or projecting "power" on the side next the eye or screen. Fig. 200 is a section of such an arrangement made by Hofmann of Paris, the plate of crystal being shown between the two hemispheres. Such a combination converges the pencil of rays to a point within $\frac{1}{8}$ inch or less of the plane surface of the first hemisphere, from which point they as widely diverge, but are re-collected by the second similar set, and finally projected through the analyser by another focusing lens or pair of lenses.[1]

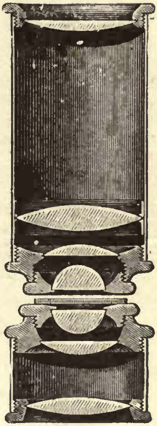

FIG. 200.—Convergent Lenses.

If the utmost possible angle be desired, a plan must be adopted which we owe to the ingenuity of Professor W. G. Adams. It consists essentially in forming the two hemispheres

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[1] The precise arrangement of the lenses has been varied by Continental opticians and physicists. Laurent, following Descloiseaux, adopts four plano-convex lenses of increasing diameter, nearly in contact, for each series, with a separate single focal power. My own first system was composed of two pairs of plano-convex lenses nearly hemispheres, which I picked up ready mounted, and adapted for the purpose. This was much improved just after the publication of the former edition of this work, by placing a somewhat larger convex "field lens" $1\frac{1}{2}$ inches behind the second series, according to an arrangement of Von Lang's described in Müller-Pouillet's *Lehrbuch der Physik.* I still think a field lens thus placed the best for projection, but for the systems themselves prefer three lenses of shallower curves: the whole arrangement being shown in Fig. 161, page 249. By moving the position of the lens H to some extent, some variation may be made in the focal power, but for extensive range of distances two powers for use at K should be provided. The size of the image can also be enlarged, if necessary, by using a concave lens as "amplifier" beyond the analyser.

The proper *adjustment* of the lenses is the chief point. The fringes are of the nature of shadows, and are so projected when the ordinary crystal into the front and back sides of a *cell*, which is filled with oil in which the crystal is immersed. This prevents the much greater divergence of the oblique rays caused by refraction from or into air, the direction in the oil being little altered. In this way the extreme angle of 90° can be collected; without the oil, extreme angles are kept within the crystal by total reflection (§ 35).

The rings and brushes can be finely shown in any microscope which possesses a draw-tube and the customary wide collar under the stage, or a sub-stage. The usual "sub-stage condenser" of N.A. 1·0. (*i.e.* angle in air of 180°) mounted over the usual polarising Nicol, answers perfectly for the first set of lenses, racked up level with the stage; or such a condenser, or Abbe condenser, may be pushed up in the usual under-stage fitting, and a glass pile used for polarising, if the Nicol is too small. For moderate angles many objectives will suffice for the second set; but a combination much like an erector must be fitted into the lower end of the draw-tube, adjusted to focus the *back lens of the objective* in the field of the eye-piece, over which an analyser is fitted as usual. I found a Reichert No. 6 ($\frac{1}{5}$) give beautiful images up to the usual angle of mica, and many immersion lenses give excellent results (used dry). For higher angles, a system should be made up instead of an ordinary objective; but as the lenses need not be achromatic, the cost of this should be small. A quarter-wave

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stage alone is used; with the convergent system, they are focused as they appear *at the back of the second system.* If the rays from the very edge of the back lens of this do not converge so as to pass through the focusing power, the edge of the disc projected on the screen will be dark. This convergence can hardly be obtained by lenses in actual contact; but a very slight distance between the second and third convergent lenses of the second system increases the convergence materially; and the large field lens increases it still more. When properly arranged the image is equally bright to the edge; and it is by slight adjustments of distance, proper proportions, and a suitable field lens, that this is to be accomplished. The analyser also must be capable of adjustment at the crossing-point of the focusing rays.

is easily inserted if required. All the range of phenomena in this chapter are therefore brought within reach of the microscopist at very little extra cost.

For a convergent apparatus very small crystals suffice, the light being converged to a mere point. Some of the best crystals can only be obtained large enough to give sections about $\frac{1}{8}$ inch across; but such are perfectly exhibited if blacked round. With an immersion lens on the microscope the figures can be seen in a small bit of a mineral section 1 mm. in diameter, which is very convenient in examining many petrological slides.

191. **Anomalous Dispersion in Bi-axials.**—The phenomena analogous to anomalous dispersion are still more remarkable and interesting in bi-axial crystals than in uni-axials. Not only are the axes, as a rule, somewhat differently inclined for different colours, but in some bi-axial crystals they do not even lie in the same plane. Borax is a good case of this kind. If a plate cut across both axes be placed in the polariscope, with the line joining its axes parallel with or across the polariser, when the analyser is crossed it will be found impossible to produce a *perfectly* straight black brush in the line of the axes; both arms are perceptibly curved, and when the long arm is vertical there is a perceptible tint on the left of the top arm, corresponding to one on the right-hand of the bottom arm. In adularia, the centres of the "eyes" for red and blue are dispersed on lines parallel to each other, perpendicular to the long arm of the cross. In other crystals, whose axes lie in the same plane for all colours, the inclination varies very greatly, and progresses in reverse order for some crystals compared with others. Thus, when the plate is turned round so that its axial rings are at 45° angle with the polarising plane (Fig. F, Plate VI.), the parabolic "brushes" are in nitre margined with red inside and blue outside, while in lead carbonate the reverse is the case. In lead carbonate and many other crystals, the dispersion of the axes is so strong, that the hyper-

bolic brushes appear only as red and blue, there being no black brush whatever; while the rings in white light assume very peculiar and beautiful forms. In monochromatic light, however, true lemniscates will be observed.

The most remarkable example of anomalous dispersion in the axes is in a few crystals such as brookite, in which the axes for red light lie in one arm of the cross, while those for violet lie in the other arm; or, in other words, the axes for the two ends of the spectrum lie in rectangular planes! Hence the figure presented even in white light somewhat resembles that of a "crossed" crystal (§ 198). Brookite is rather difficult to project clearly, owing to its red colour; but similar phenomena may be seen in the *sel de seignette*, or triple tartrate of soda, potass, and ammonia, which is colourless and transparent. Viewing or projecting this crystal, with a red and blue glass alternately in the large slide-stage of the polariscope, the rectangular planes of axial dispersion will be readily seen; and if a coloured glass can be procured of such a shade and density as cuts out the middle of the spectrum and leaves the blue and red only, the two systems of fringes can be seen superposed. In Plate I. (Frontispiece) the figure of brookite or *sel de seignette* in white light is shown at A, while at B is shown the extraordinary modification produced when the crystal is projected or examined by light containing blue and red only.[1] In green light the crystal is nearly uni-axial, the rings, however, being more square than circular.

192. **Theory of Bi-axials.**—The theory of bi-axial crystals was gradually elucidated by the labours of Brewster, until Fresnel framed the one simple general conception of three *axes of elasticity* in three rectangular directions. If all these were equal, rays proceeding from a point in the crystal in

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[1] It is rather difficult to get sufficient light for projection. I have succeeded best by using two or more gelatines selected with a prism, and cemented between glasses with balsam and benzol. They are much more transparent thus mounted.

all directions would at the same moment reach the surface of a sphere, and the crystal could have no double refraction. If two were equal, both being perpendicular to the third, *all* perpendicular to that third must also be equal, and the crystal must be uni-axial. If all three were unequal, it was shown by a beautiful mathematical analysis that the crystal must be bi-axial; the axes of no double refraction being simply resultants of the three different elasticities, both lying in the plane of the greatest and least elasticities, at an *angle* dependent on the relative magnitude of the third or mean elasticity. This beautiful theory was shown to be exactly what ought to follow from the simple assumptions of the undulatory theory, and to account for every detail of the known phenomena; but several necessary deductions followed, which did not become apparent till after Fresnel's death. It is interesting to see how these purely theoretical deductions were justified.

193. **Mitscherlich's Experiment.**—It followed, first of all, that any alteration of the *respective elasticities* must necessarily alter the inclination of the axes; and should the change go so far that the mean elasticity became first equal to either of the others, and then reversed in relative magnitude compared with it, the crystal must first become uni-axial, and afterwards bi-axial with axes in a plane at right angles to the first. Now we have already seen (§ 132) that heat will effect such changes; selenite especially being considerably altered in relative dimensions and relative elasticities, by a very moderate rise of temperature. Professor Mitscherlich therefore took a plate of this crystal cut so as to show both the axes; and exposing it gradually to a heat not exceeding that of boiling water, he had the satisfaction of seeing the two systems of rings gradually approach each other. A point was soon reached at which they coincided, and *the crystal became uni-axial*; and the moment after the axes began to open out in a direction at right angles to the former.

This fine experiment is projected with the greatest ease, the only difficulty being in cutting the crystal. Unlike mica, whose natural laminæ are at right angles to the median line between two axes, the laminæ of selenite include it, and the crystal has therefore to be cut across its cleavages. A plate of copper or brass, A (Fig. 201), has a hollow turned in its centre so as to leave only a very thin plate of metal to support the crystal, an aperture sufficiently large for the rays being bored in the thin plate. The crystal, rather larger than the aperture, should be set in a disc of cork (shaded black in the figure) and shaped to fit the hollow: the whole being covered by another thin metal plate, C. The arrangement is then placed on the stage of the projecting apparatus, so that the ends of the metal project well, and these ends are heated by spirit-lamps, or by one lamp alternately.[1] Suppose the crystal is so arranged on the stage that the two systems of rings appear at first to stand vertically upon the screen. As the slide warms, there will probably be a mist for a minute or two, owing partly to moisture on the lenses, and partly to heating of the air between the laminæ of the crystal; and the heat should be applied gently till this clears away, as it will soon do. Then the axes will gradually be seen to approach, till the rings exactly resemble those of a plate of calcite;[2] and after this they open

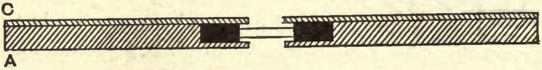

FIG. 201.—Slide for Mitscherlich's Experiment.

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[1] Another good way is to cut a hole, large enough to hold the crystal loosely, quite through the middle of a slip of brass the same thickness, retaining the crystal by doubling over both sides a piece of card in which are cut holes too small for the crystal to fall through. The ends of the brass are better bent away from the stage. A special slide with projecting ears for heating is made for the purpose. Crystals cost 3*s.* to 5*s.* each.

[2] At this stage the lamps had better be removed till it is seen how things go. The metal slide will probably have taken up sufficient heat to go on further without more; and a very moderate excess of heat will calcine the clear crystal into mere plaster of Paris.

out again in a *horizontal* direction. On the lamp being removed the whole process is reversed.

194. **Conical Refraction.**—A more striking proof of the truth of Fresnel's hypothesis was discovered by Sir W. Hamilton. On projecting the wave-shells geometrically according to this theory, they were found to resemble those partially shown in Fig. 202 (from *Müller-Pouillet*). Now if a single ray traverses the crystal in the line P P, or P′ P′, on reaching the surface it is refracted into air, as usual, from the perpendicular. That perpendicular has reference to the *tangents of two different curves*, and so produces two different refractions. If the shells are completed, however, as in a solid model, it is found that the four points P are *cusps*, or hollows resembling that surrounding the stem of an apple;[1] and it therefore follows that on emergence from the point P the ray must be spread out into a *diverging conical shell of rays.* Here, therefore, was a mathematical prediction of a phenomenon never foreseen by Fresnel, who had confined himself to the single plane through the points P shown in the diagram; and such a kind of refraction was not only opposed to all past experience, but to all apparent probability.

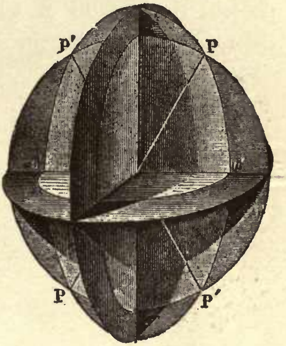

FIG. 202.—Bi-axial Wave-Shells.

At Sir William Hamilton's request the matter was tested by Dr. Humphrey Lloyd in a crystal of arragonite. The lines P P and P′ P′ are lines of single velocity, and coincide *nearly* with the optic axes, but not exactly, their angle being nearly

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[1] It is very difficult to give a clear idea of the complicated wave-surfaces of bi-axials to ordinary readers. Some may derive assistance from another and differently shaded figure, which will be found under the article "Undulatory Theory," in *Chambers' Cyclopædia.*

20°. A plate is needed $\frac{1}{4}$ inch or a little more in thickness for this experiment, cut across both axes. Then a thin metal plate with a very small aperture was fixed on one side of the crystal plate, and a movable one placed on the other, while the crystal was fixed in a frame movable by a screw so as to present the crystal at various angles. A beam of light was then condensed on the aperture O (Fig. 203) at an angle of 15° or 16°, so as to be refracted in the direction of O M, or O N, which is nearly an optic axis.[1] When the adjustment was complete, on looking through the second aperture, instead of two apertures a *brilliant ring* of light appeared to the observer; Sir William Hamilton's prediction being thus justified to the letter!

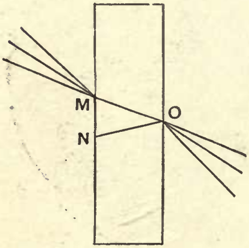

FIG. 203.—Conical Refraction.

In a similar way it was shown that if a very small pencil of parallel rays (sensibly apparent as a single ray) were incident at O, so as to be refracted exactly into the optic axis, it should be divided into an *internal* cone within the crystal, which on emergence would resume parallelism and appear as a *hollow cylinder* of rays, since the cone would reach the wave-shells at the points where the common tangent-plane touched them in a small circle surrounding the cusp. The cone in this case was so small that the phenomena were much more difficult to observe: but by adjusting the crystal with extreme care, this prediction also was verified in actual fact.

The easiest way of observing conical refraction is to substitute for the aperture O, a *fine slit*, in the plane of the optic axes. Then if the aperture M be fixed on the other face

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[1] The *convergence* of the rays, to produce a single ray within the crystal, must of course correspond with the calculated *divergence* on leaving the crystal. The optic axis is the normal to the common tangent-plane touching both wave-surfaces.

tolerably near the correct position, on gradually tilting the crystal in the plane of the axes, when the right point is reached the slit will be seen to split in the middle into two oval curves. The experiment is only one for the student, the small pencil of light not permitting of projection.

195. **Relation of the Axes in Uni-axial and Bi-axial Crystals.**—It further follows that, according to this theory, the optic axis of a uni-axial crystal by no means coincides in character with one of the axes of a bi-axial; but is simply a limiting case in which both these axes coincide. Professor Mitscherlich's experiment is one beautiful proof that this is the case: and further optical proof of it will be found in § 206, where it will be seen that important optical phenomena of both axes in a bi-axial, are preserved distinctly in uni-axial crystals.

196. **Composite, Irregular, and Hemitrope Crystals.**—Twin or macled crystals are found very often: a slice of nitre, for instance, can be found without difficulty that will exhibit four systems of rings. Calcite is often found in which thin layers *crystallised in the opposite direction* are frequent. A large crystal of such calcite, if a ray is sent through it to the screen, gives a greater or less number of coloured images: the interrupting film answering to the films of mica or selenite in our earlier experiments, and the thicker masses to analyser and polariser—the whole being a sort of natural Huygens's apparatus fixed in one position, with a film between the two prisms. But far more beautiful effects are obtained if a plate be cut across the axis, including one of these films or planes, and it be examined in the convergent light. The system of rings is then modified by glorious brushes of coloured light, which radiate somewhat like the spokes of a wheel; and the pattern of the rings themselves may be varied in a beautiful manner. If such a plate is cut thin enough to exhibit in the very convergent system, on moving it about so that the conical pencil may traverse different points in succession, the phenomena will

sometimes vary in an extraordinary degree. Composite quartz crystals have already been referred to (§ 172).

These effects may be partially imitated by placing a film of mica or selenite between two thin plates of calcite cut across the axis; and are perfectly imitated if the calcites are ground into a pair of wedges making together a parallel plate. Pieces of calcite subjected to strong pressure and then cut, also give fine irregular phenomena; or a plate may be projected while squeezed in a small vice.

Other irregularities are often found. Ferro-cyanide of potassium (prussiate of potash) for instance, is properly a uni-axial crystal. But crystals can be found, out of any sample, of which slices gives bi-axial effects: and yet others, which give symmetrical coloured patterns, which are very beautiful, though crystallographically irregular.

197. **Mica and Selenite Combinations.**—Nörrenberg to some extent demonstrated the cause of these beautiful phenomena, or at least closely imitated them, by combining films of selenite with films of mica, a selenite being placed between two micas to form one "element," as he called it. The micas were parallel: and in some combinations the principal axis in the selenite was parallel to the mica axis, and in some across it. In one case he called the triple film a positive element, in the other a negative element; and these may be superposed, either parallel or crossed, in any way, though Nörrenberg confined himself to symmetrical combinations.

It will be manifest that the effect of these combinations is very complicated; but the results are so beautiful, and so instructive when studied with care, that I attempt some elementary explanation, and give two pairs of examples; each example of a pair, as in the case of the brookite crystal, containing *precisely the same material*, but differently arranged (C D, E F, Plate I. *Frontispiece*). If we call the three rectangular axes of elasticity in any crystal x y z in order of their magnitudes, then a selenite film contains x and z, while the intermediate one y is normal to the film. In mica, on the other hand, y and z are in the plane of the film, and x is normal to it. Thus if we conceive a cube built up of films, in mica the rings are seen in the face of the films; in selenite on two opposite sides of the cube represented by their edges. It is evident that such relations of the retardations, must in convergent light produce very beautiful chromatic phenomena.

The simplest of these are with parallel micas only. If we take one Nörrenberg element alone, *i.e.* a single selenite between two micas, the ordinary figure is not very greatly altered, beyond a great widening and enrichment of the colour-fringes; and there is not very conspicuous difference between them, whether the principal axis of the selenite is parallel to that of the mica or crosses it.[1] But let us give the selenite functions of elasticity more effect. In C D, Plate I. (*Frontispiece*), are shown preparations, each of which is built of five parallel half-wave micas (half-wave is thin for this class of work) with four parallel selenites interleaved; but in C the selenites cross the micas, and in D are parallel with them. It will be seen that in both cases we have peculiar curves having their origin approximately in the mica axes, but reversed in character; and that the tendency in C is to bring the centres of the two systems closer together, and in D to draw them farther apart. This is what we should expect. If however we employ red instead of white light, we get approximate lemniscates only, but with the rings closer in the case of C. All through, in these preparations, a most extraordinary difference will be seen in the phenomena when either red or blue light alone is employed.

I give two more examples. In E F of the same plate are shown preparations each built up of four of Nörrenberg's "negative" triple elements; *i.e.*, the selenite crosses the micas in each. I owe to Mr. Fox the practical hint which I

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[1] The films are considered "crossed" when the two, if of same tint of same order, counteract each other in parallel light.

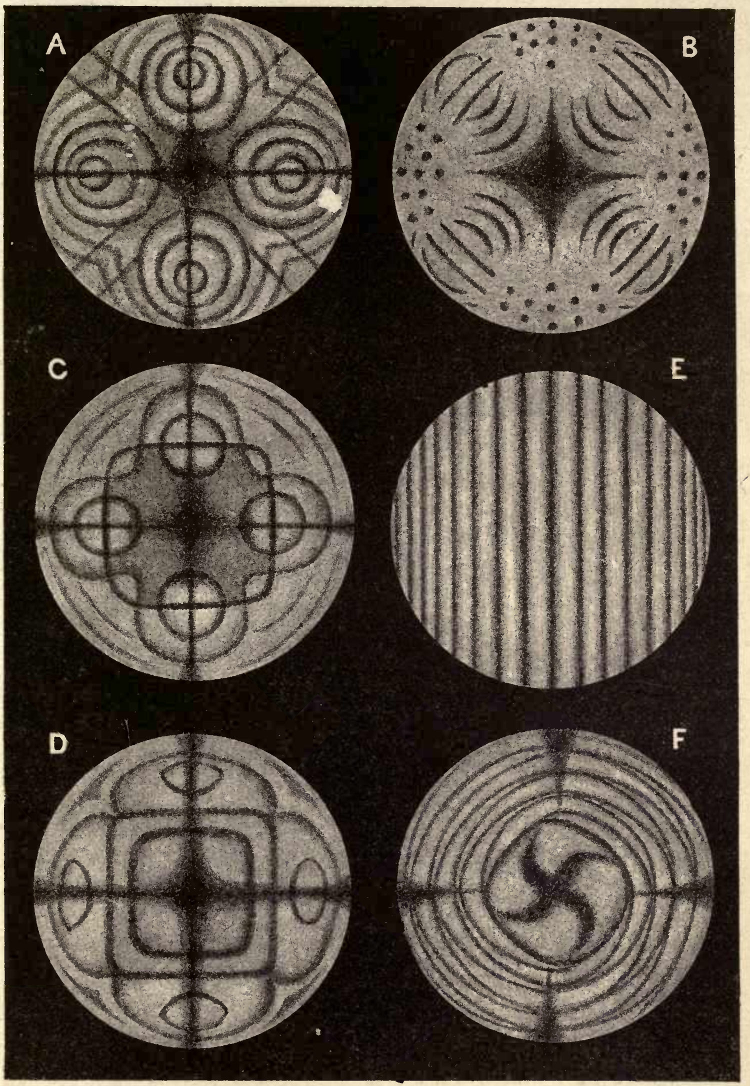
gladly give in turn to others, that one of the best thicknesses of selenite for quadrilateral preparations is $1\frac{5}{8}$ waves, which gives the rich orange inclining to red in the second order of the mica wedge. The figures shown are built of these, with $\frac{7}{8}$ wave micas. The preparation F is made by superposing two of the elements parallel, and crossing upon them two others parallel; while E is constructed of the very same four elements, but crossed one-and-one alternately.

Positive elements give utterly different figures. Positive may also be crossed on negative; and the films may be varied and crossed in all sorts of ways. Very fine figures not quadrilateral are produced by crossing two parallel elements between single elements; and a very simple effective preparation is made by crossing a negative element, made of $1\frac{5}{8}$ selenite and two 1-wave micas, between two 1-wave micas alone.

These preparations are perhaps the most difficult of all to construct; selenite not being easy to split nicely, to begin with, and the difficulty of getting the axes of micas and selenites *exactly* parallel or rectangular, being very great. If they are not exact, the black brushes are not straight and sharp. Any fault in this is a great eyesore, though the beauty of the figure otherwise remains; and a good proportion are spoilt from this cause. The manipulation varies. Mr. Fox built square cells with strips of glass on square glass plates, in which his films were inserted. Messrs. Steeg and Reuter prepare theirs between small square glasses, which when cemented and dry are mounted in square plates of cork like their crystals. The method I prefer is to cut the films in $\frac{5}{8}$ inch squares; superpose them, with a small drop of benzol-balsam on each, in the centre of a microscopic glass slip, and cover with a micro cover-glass. If truly cut they are easily got pretty true after all are laid down, by using a steel point in each hand; and may be left to dry with a very small weight, such as a printer's type, standing on each. Such slides can be kept in ordinary micro slide-boxes, which is convenient. The mica sheets should be scratched

Pl. 7.

CROSSED AND SUPERPOSED CRYSTALS.



A. *Two Micas crossed*

B. *Ditto. axes rotated 45°*

C. *Four Micas crossed*

D. *Eight Micas crossed*

E. *Savart's Bands*

F. *Airy's Spirals*

N.B. A.C.D. *are* B.C.D. *of Norremberg's series, showing progress towards the Uni-axial form.*

into true squares all over, any portions not the *exact* thickness of the main part of the sheet being defaced for rejection; the sheet can then be cut up with the large scissors. Selenites can only be cut with the single blade, used gently.

Negative elements may however be imitated to some extent by mica films alone; and there is no difficulty with these about accuracy, because so long as the axes are marked *alike* on two sheets, squares will *cross* truly, even if the marks themselves are not quite true to the axes. Ternary elements may be made by crossing $\frac{1}{8}$-wave mica-films between two thicker ones. Using $\frac{5}{8}$ wave or $\frac{3}{4}$ wave for the thicker micas, the student may construct very beautiful preparations in this way with no difficulty, crossing either doubles like F in Plate I., or single elements alternately like E in same plate, or two crossed between a pair of single elements.

198. **Crossed Crystals.**—These give beautiful effects, but also require the convergent system. Two plates of mica are easiest put together, and give four systems of rings (A, Plate VII.), or when the preparation is rotated 45 degrees show beautiful hyperbolic curves in the centre (B). Crossed arragonite or topaz gives similar effects. Crossed titanite is very effective, owing to its peculiar dispersion.

Two ordinary films of selenite 1 mm. or more thick, too thick to show any colours alone, when crossed give hyperbolic curves in convergent light; as do two quartz-plates cut parallel to the axis.

199. **Nörrenberg's Uni-axial Mica Combinations.**—The most interesting, however, of this kind of combinations are also due to Professor Nörrenberg. Mica is found occasionally *uni-axial;* and bi-axial specimens are found of all angles from 0° up to 75°, in this respect resembling the ferrocyanide of potassium. Senarmont had proved by experiment the results of combining salts crystallising in identical forms geometrically opposite. Thus, the double tartrate of soda and potash (Rochelle salt) crystallises in prisms; and if we replace

the potash by ammonia, we get similar prisms. Both are bi-axial crystals with an angle of 76°, and a peculiar dispersion of the axes pointed out by Sir John Herschel is the same in each. The one optical difference is, that the plane of the optic axes passes through the smaller diagonal of the rhomb which forms the base of the prism in one case, and of the longer diagonal in the other. Senarmont showed that by crystallising mixtures of the two double salts, the angle of the axes could be diminished ; and that with a certain proportion the crystal became uni-axial like calcite ; though, owing to the great dispersion of the axes, it can only be strictly uni-axial for one colour in any given combination, whence the peculiar dispersion noticed in § 191.

Hence Nörrenberg supposed there might be two kinds of micas ; isomorphous, but geometrically opposite : and that the variable angles, and uni-axial micas, might be produced by superpositions of infinitely thin films of each, in different proportions and positions.

Experiment seemed to justify this. A number of thin films of mica crossed alternately at an angle of 60°, reduced the angle of a bi-axial mica from about 70° to about 46°. But far more interesting was the gradual passage to the uni-axial form when the films were crossed at 90°. Denoting a thickness of one wave by w, Nörrenberg constructed the following series, where the figure under the alphabetical letter denotes the number of films, and the bottom fractions the thickness, the total of all being three wave-lengths of retardation.

A	B	C	D	E	F
1	2	4	8	12	24
$3w$	$1\frac{1}{2}w$	$\frac{3}{4}w$	$\frac{3}{8}w$	$\frac{1}{4}w$	$\frac{1}{8}w$

In this series of preparations, A of course gives the ordinary bi-axial phenomena. B gives four systems of rings with hyperbolic curves (A, B, Plate VII.). In C we get the first approach to the uni-axial character, which becomes more and more perfect as we proceed, until at last there is absolutely no difference between the phenomena and those of a plate of calcite.

There is no magic in three exact wave-lengths as the total thickness, but approximately it seems the best total. All that is necessary in making these instructive preparations is that, as before described, all the films of any one preparation be of the same thickness, and the two polarising axes, in each alternate film, accurately crossed. The method of obtaining both conditions has been already given. I prefer to add an intermediate preparation of six films between C and D, which gives a more complete black square ring. Then eight films give two such rings, the inside one more circular and the outer one square; while twelve films give three rings, sixteen four rings, and so on.

Very beautiful and instructive preparations can be made by varying the thicknesses of these crossed films. Eight crossed of Nörrenberg's thickness we have seen to give us two rings, the outer one rather square (D, Plate VII). But if we cross eight *thin* films—say $\frac{1}{8}$ wave—we get circular rings even with this number, and twelve give us really fine rings, only broader and bolder than the 24 films. On the other hand, let us now cross both 4 and 8 of *thick* films—say 1 wave thick. The rings now entirely disappear, and the coloured fringes are all turned the other way, their convex sides towards the centre. A really splendid figure is produced by 12 crossed films $\frac{3}{4}$ wave in thickness.

Squares of mica may also be cut of the same size as the others, but with the axes at angles of 45°, and combined with the foregoing. The following will be found instructive, the lines showing the successive positions of the mica axis in films successively superposed.[1] The first four are $\frac{1}{2}$ wave films: the

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[1] I take them from my paper "On Optical Combinations of Crystalline Films," in *Proc. London Physical Society*, 1883.

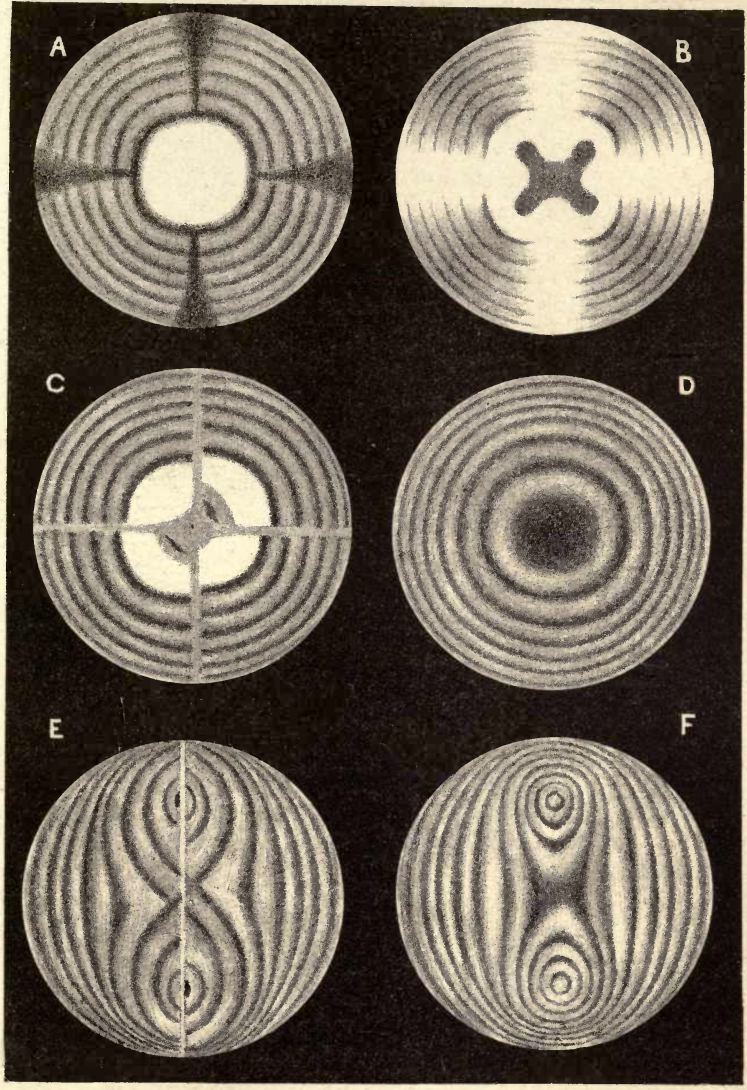
other four $\frac{3}{4}$ wave and whole-wave films : a cross denotes a pair crossed.

1. | \ | — \ — | \ | — \ —
2. | \ — | \ — | / — | / —
3. || — || — | = | =
4. | — | — | — — | — | — |
5. | — | × | — |
6. + + × + +
7. + × + ×
8. | / — \ | / — \ (*i.e.*, successively rotated 45°).

200. **Airy's Spirals.**—Owing to the peculiar character of the doubly-refracted rays in quartz, if a plate of "right" and another of "left," of equal thickness, be placed together in the crystal stage and analysed by convergent light, the colour is not exactly neutralised, as it is in parallel light, but we get a most beautiful quadruple spiral (shown in F, Plate VII.). These spirals were discovered by Mr. Airy, and are called by his name. They form a most beautiful screen projection, when the thickness is adapted for the convergence employed. About $\frac{1}{16}$th of an inch to $\frac{1}{8}$ inch each is a good thickness for each plate, for the objective alone. A *single* quartz plate will show the spirals in Nörrenberg's "doubler." If truly cut across the axis, it may be laid on the bottom mirror, holding a lens about $1\frac{1}{2}$ inches diameter, and 2 inches focus above it, so as to converge and re-collect the rays which have twice passed through the plate; but should the quartz not be quite true, the lens must be laid *on* it, and both together adjusted by hand till accurate spirals appear. This experiment is particularly interesting as showing the reversal of the rotation described in § 177.

Pl. 8.

CIRCULAR POLARIZATION IN CRYSTALS.



A. *Quartz, with analyser crossed.*
B. *" analyser parallel.*
C. *Calcite, polarized circularly.*
D. *Calcite polarized & analysed circularly*
E. *Mica polarized circularly*
F. *Do. polarized & analysed circularly*

Reusch's artificial mica-film quartz presents all these phenomena *perfectly*. In convergent rays a single one exhibits the rings with coloured centre, and black brushes as the centre is receded from; and a pair of right and left superposed give perfect Airy's spirals.

201. **Savart's Bands.**—If slices of quartz are cut neither parallel to axis, nor across it, but at 45° angle, such slices singly show hyperbolas; but if two such slices are crossed at right angles, these become in convergent light straight lines, called "Savart's bands," and such a combination is a very sensitive test of polarised light, the least degree of polarisation making the bands visible. Slices of calc spar split naturally and crossed give the same results (E, Plate VII.).

It may be mentioned here, that in these phenomena, as in all others, if the thin glass analyser, Fig. 166, be used instead of the Nicol, the complementary image to that on the screen will always appear on the ceiling. Complicated as the phenomena may be, such an analyser never fails thus to sort them out rigidly into two complementary sets.

202. **Crystals in Circularly-Polarised Light.**—Having traced the general phenomena of crystals when examined in convergent plane-polarised light, we next proceed to examine the appearances they present in circularly-polarised light; being prepared by our previous experiments with this description of light, for some interesting variations of the phenomena.

We place first a large quarter-wave plate (in its depolarising position) in the ordinary slide-stage of the polariscope; and a plate of calcite cut across the axis in the crystal stage. The calcite loses its black cross, as we should expect, the cross being replaced by a thin (mere lines) nebulous *grey* cross which rotates with the analyser, on either side of the arms of which alternate quadrants of rings are *dislocated*, as in C, Plate VIII., the light rings in one quadrant being opposite the dark parts in its neighbours. This figure does not change in the least as the analyser is rotated; the quadrants and rectangular nebulous lines simply rotate with it.

Bi-axial crystals give similar phenomena, the arms of the cross which pass through the axes being replaced by grey lines, on each side of which the *semicircles* of each system of rings are dislocated. This is most distinctly shown by placing in the crystal stage a plate cut across one axis only, as in the nearly circular rings of one axis in sugar-candy. If the quarter-wave plate be rotated 90°, the quadrants or semicircles which were first the smallest, will gradually become the largest, and *vice versâ.* Precisely similar effects will be found if the large quarter wave plate be withdrawn, and the light be *analysed* circularly through a smaller one, placed anywhere between the crystal and the analyser. The most convenient position for an analysing plate is near the field lens H in the polariscope shown in Fig. 161.

203. **Explanation of the Phenomena.**—This strange dislocation of the rings is easily explained, if we remember that the circularly-polarised ray is compounded (after passing through the mica-film) of two rectangular plane vibrations, one of which is a quarter-undulation in phase behind the other—or in other words, referring to Fig. 180, one vibration in the middle of its swing acting upon another at the moment of rest, as represented by the arrows in that figure. In the quarter-wave plate, supposing the plane of polarisation to be vertical, the vibrations are diagonal; and may be represented by the diagonal pairs of arrows in Fig. 204. Let this figure represent the plate of calcite with polariser and analyser crossed: in each quadrant the circularly-polarised ray, on entering the crystal, is doubly refracted into its rectangular components, one of which *enters* the plate a quarter-undulation behind the other. But we have already seen (Fig. 197, § 183) that the crystal itself doubly-refracts any non-central ray into two rectangular components, represented by radii and tangents to the circles; and in every uni-axial crystal, either the radii or the tangents are

uniformly the most retarded—in the case of calcite the radii. Now in each order of colours or "ring," there is some position or distance from the centre where the retardation is either a half-wave or an odd multiple of a half-wave; and on the other hand, mere inspection of Fig. 204 shows that in the middle of each quadrant the two plane vibrations emerging from the mica film (and after composition into a circular orbit, again decomposed) coincide with the two vibrations—radius and tangent—in the plate of calcite. But it will be seen, that whereas in the calcite alone, all the radii are alike retarded at given intervals one or more half-waves behind their tangents, it is different with the mica retardations. In two quadrants the vibrations, A B, A B, coincide with radii; while in the alternate ones, *a b*, *a b*, they coincide with tangents. The *uniform* annular half-wave retardations of the calcite, are therefore in two quadrants augmented by an additional quarter-wave retardation from the mica; and in the intermediate quadrants diminished by a quarter-wave retardation of the opposite polarising plane. The result is therefore a dislocation by two quarters, or half a wave; which brings the bright rings of one against the dark rings of its neighbouring quadrant.

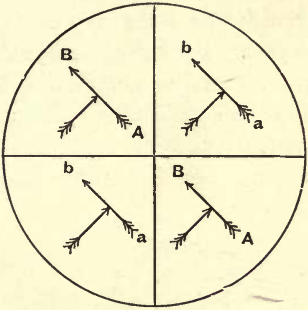


FIG. 204.—Effect of Quarter-Wave Plate.

This is simply demonstrated by placing before a concave selenite in the stage, a quarter-wave film in four reversed sectors, with the lines of section vertical and horizontal, but the mica axes at 45°. Here we have the quadrants of rings in the selenite expanded and contracted in an analogous way. If we place the selenite first in the stage, and superpose on it the quarter-wave preparation B in Fig. 188, we have expanding and contracting quadrants, with unbroken rings in two positions. But if we superpose the same B-plate upon a disc of chilled glass, we now apply the retardations equally, owing to their alternate arrangement, to either the radial or tangential vibrations in each quadrant; and accordingly there now occurs no dislocation at all, but the rings expand or contract as the analyser is rotated, remaining perfectly concentric.

204. **Result of Polarising and Analysing Circularly.**—Let us now place *both* quarter-wave plates in their depolarising positions, and the calcite in the crystal stage between them. Another very beautiful modification follows. With analyser crossed or parallel, all cross lines or dislocations have vanished, leaving only perfect *circular* coloured rings (D, Plate VIII). But as the analyser is rotated, alternate quadrants *expand* and *contract* in a beautiful manner, so that at 45° we have the dislocated quadrants, and at 90° the *complementary* perfect rings to those in the first position; the successive appearances being represented in Fig. 205, A, B, C. The appearances in a bi-axial, such as nitre, are analogous, all brushes having vanished, and each axis being surrounded by unbroken rings (F, Plate VIII.).

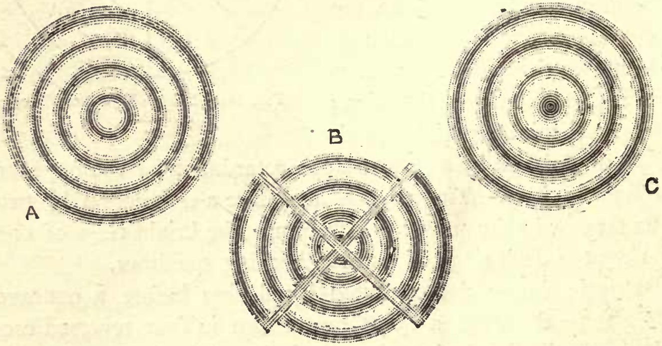


Fig. 205.—Uni-axial Crystal Circularly Polarised.

Lastly, at the point when the rings are perfect and unbroken, if either the crystal stage with all it bears—crystal, quarter-wave plate, and analyser—or even only the quarter-wave plate and analyser, be rotated, no change whatever occurs; the rings *remain* unbroken, and all trace of polarising planes is completely lost, as theory would lead us to expect. The most marked demonstration of this is to rotate the whole affair with a bi-axial, such as nitre, or arragonite; since nothing can more strikingly show the perfect independence of any plane of polarisation than the fact that such a bi-axial, which ordinarily changes so greatly when the crystal itself is rotated till its two axes stand at 45°, (see D, E, F, Plate VI.), shows no change whatever when rotated as here described. The systems of rings round the two axes rotate round each other; but remain in all positions unaltered, and no brushes appear.

It may be worth while to remark, that a circular chilled glass in the optical stage behaves exactly like a uni-axial crystal in the crystal stage, under circularly-polarised light. Placing next the polariser a quarter-wave plate, and then the chilled glass, the usual black cross is replaced by the thin nebulous grey cross, which rotates unaltered with the analyser; and adding the second quarter-wave plate, the analyser at 0° and 90° gives perfectly unbroken and complementary rings, while in intermediate positions the alternate quadrants expand and contract during the transition.

205. **Quartz in Circularly-Polarised Light.**—When quartz is placed in the crystal stage and examined with a single quarter-wave plate, the curious double spiral shown in F, Plate IX., is seen. The number of spiral rings depends on the thickness of the plate and convergence of the rays. With two quarter-wave plates—one each side of the quartz—we get perfect rings, as with other uni-axial crystals. The significance of this phenomenon will appear in the next section.

206. **Spiral Figures.**—It is remarkable that in the foregoing experiments the rings surrounding a single axis of a bi-axial crystal, when polarised and analysed circularly, appear as

perfect circles; or are apparently precisely similar to those surrounding the axis of a uni-axial crystal. From this the conclusion might be drawn that one axis was similar to the other in character. We have seen already (§ 195) that this could not be the case according to Fresnel's theory; and Mitscherlich's experiment (§ 193) is a beautiful demonstration of the gradual approach of the axes of a bi-axial until the uni-axial form appears as a limiting case, in which both axes coincide. It appeared to me, however, desirable to seek for further experimental demonstration that the axis of a uni-axial crystal was not only such a limiting case, but actually did still retain within itself in some visible form the optical characteristics of the two axes thus brought into coincidence. This object seemed most likely to be obtained by the aid of quartz or some similar substance having properties of rotary polarisation. Such substances having two different *axial* velocities or waves, capable of being brought into interference; and the two axes of a bi-axial being dissimilar from the nature of the case, one of them having the character of a principal axis and the other being secondary to it; it seemed probable that the two axes might be made to exert some kind of differential or selective action upon the two sets of waves passing through the rotatory substance. This expectation was confirmed by the curious double-spiral (first noticed by Mr. Airy[1]) as displayed by quartz when placed in somewhat convergent circularly-polarised light, (§ 205), the true cause of which appeared to me to be connected with this very matter, as we shall see that it is.

I placed therefore in the apparatus first, next to the polariser, a quarter-wave plate; then, in the crystal stage, a calcite; and next to this, also in the crystal stage (made with a wide opening to admit extra plates) a plate of quartz from 5 mm. to 7½ mm. thick. The result is the beautiful system of double spirals, mutually enwrapping each other, shown in A, Plate IX. and which changes in colour, or appears to approach or recede

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[1] *Cambridge Transactions*, 1831.

from the centre, as the analyser is rotated ; though there are of course only certain opposite positions of the polariser (related to that of the quarter-wave plate) which produce them. The point to be here remarked is the *double* spiral observed in the *uni-axial* crystal.[1]

This figure however so closely resembles, in all but the number of its convolutions, that observed by Mr. Airy in quartz alone, in convergent light, that it might possibly be due to the quartz itself. To determine this point it is necessary to test other crystals, and to get rid of any such possible cause. We therefore replace the calcite in the crystal stage by a plate of sugar cut across *one* of its two axes.[2] The result is the spiral shown in B, Plate IX. It will be observed that with this single axis of a bi-axial, we no longer have the double spiral, but a *single* one, corresponding strictly to the theoretic relation of which we are seeking proof, and also showing that these figures are not due to the quartz in itself, but to the selective action of our other crystals upon its two axial waves and their interferences.

A single axis being thus tested, we replace the sugar in the crystal stage by some bi-axial, such as nitre, cut at right angles to the median line between both axes. The result is the double spiral shown in C, Plate IX. The relation still holds good ; each axis has its own spiral, and the two now mutually enwrap each other as in the calcite.

To examine crystals with wider angles, we must of course employ the convergent system. But a moment's reflection will show that we must rather alter our other arrangements. In such strongly-convergent light, the rings and spirals proper to the *quartz itself*, which have not appeared in the moderate

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[1] These spiral figures were first publicly demonstrated at a meeting of the Physical Society of London on November 12, 1881, having been discovered and projected before a few friends two years previously.

[2] This crystal is peculiarly suitable for the purpose, having very little axial dispersion, so that one of its axes, if truly cut, gives sensible circles.

convergence so far employed, would overpower and distort those belonging to the crystals under examination (a single experiment will show that they do). It is moreover well to demonstrate absolutely that the figures are in no way due to any effects of *convergent* rays traversing the quartz, but solely to selective action upon the right-handed and left-handed waves traversing it axially. We therefore reverse our arrangements, placing a large plate of quartz, say $7\frac{1}{2}$ mm. thick, next the polarising Nicol, in parallel light, and introducing the quarter-wave plate between the crystal to be examined and the analyser. Of course, as it is the analyser which is now related to the quarter-wave plate, the spirals only appear in opposite positions; while on the other hand, with analyser in those positions, they only move and change in colour as the *polariser* is rotated.[1]

First we take again the small angle of a nitre crystal, but which, for this strongly convergent light, must be cut much thinner than the former. The result is shown in D, Plate IX.; where it is to be observed that we can hardly distinguish its spirals from those of the calcite (A, same plate). They are just a little drawn out into an oval form, precisely as we should expect; and that is all. Arragonite, with a wider axial angle of about $18\frac{1}{2}$ degrees, shows a spiral of several turns round each axis (E, Plate IX.), but still mutually enwrapping each other at last; and finally mica, or sugar, or other crystal with angle of say 45° to 60°, shows still more numerous convolutions, but still preserving the same mutual relation. Only crystals which, owing to peculiarities in their double refraction for various colours (§ 191), do not show in the ordinary manner tolerably complete lemniscates, for the same reason fail to show these figures.

That the spirals are due to selective action upon the

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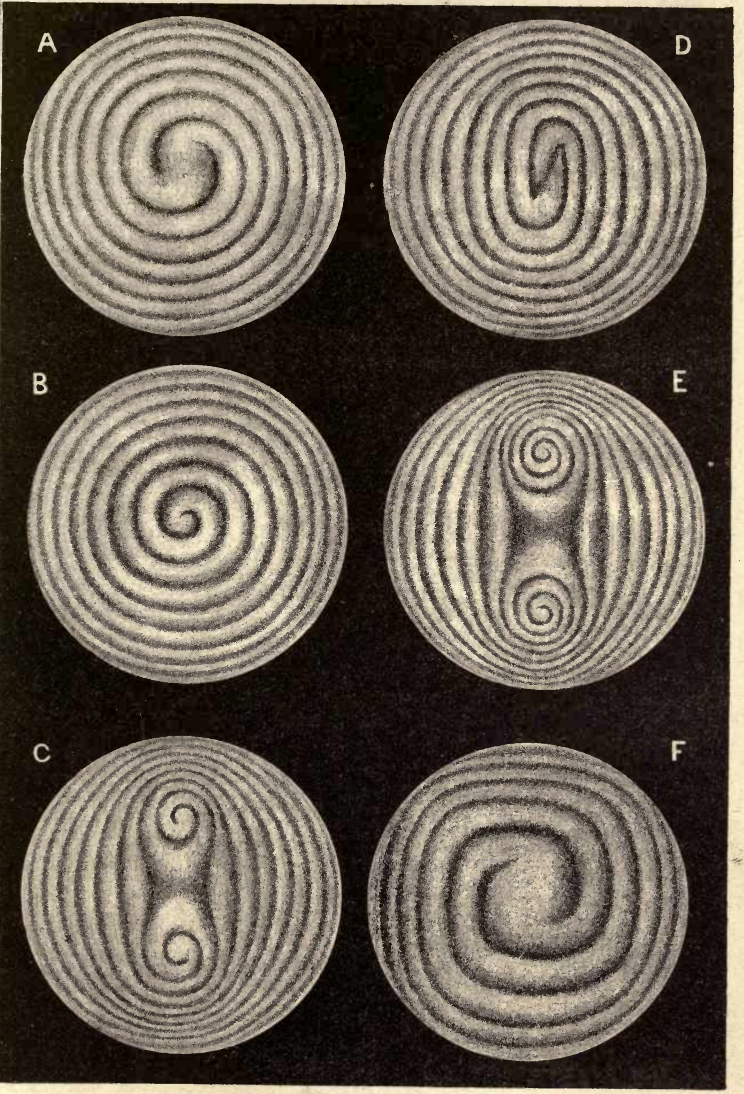
[1] This arrangement might have been adopted all along; but the experiments are given as first made, in order to show how each point was successively determined.

Pl. 9.

SPIRAL FIGURES.



A. *Calcite*
B. *Single Axis of Sugar*
C *Nitre*
D. *Thin Nitre, in highly convergent light*
E. *Arragonite,* *Ditto*
F. *Quartz*

coloured components of the two axial quartz waves, is shown by the fact that they are not seen at all in homogeneous or one-coloured light.

We next examine a crystal of selenite gradually heated, thus repeating Mitscherlich's beautiful experiment, but with this additional method of analysis. Care is required to produce equally perfect ring-systems round both axes, the least excess of heat on any side of the crystal of course causing distortion. This can however be avoided. We first obtain two spirals exactly similar to those of E, Plate IX. As the axes approach and coincide, the spirals also approach in their centres, until at the point of coincidence they exactly resemble those of the calcite (A, Plate IX.). And finally they re-open in a direction at right angles to the former. All through we have a *double* spiral; and we can only get a single one by taking separately *one* of the axes of a bi-axial; the axis of a uni-axial always preserving what we may call its twin character. Thus we have the ocular demonstration sought, of the relation predicated by the theory of Fresnel between the axes of the two classes of crystals.

But the reason is also thus demonstrated of the spirals observed by Mr. Airy in quartz itself (F, Plate, IX.) when examined in convergent circularly-polarised light. We see that the quartz, considered as an ordinary uni-axial crystal, is able, owing to its peculiar and additional effects upon plane-polarised light passing through it axially, *to show its own spirals*, which of course are double. These are not seen at all in parallel light; and on the other hand, if we employ extremely convergent circularly-polarised light, they become as numerous and distinct as those of the calcite.

A crucial test of this view of the case readily suggests itself. We can represent our quartz artificially, as it were; since many liquids act similarly (§ 175) upon a plane-polarised ray. If therefore we take a column of such liquid of sufficient length, and any ordinary uni-axial crystal, the one will represent the axial properties, and the other the ordinary doubly refractive properties of the quartz; and the two ought to give us double spirals; in fact an adequate column of liquid ought successfully to replace the quartz in all the foregoing experiments.[1]

The rotatory effect of liquids is so inferior to that of quartz, that it is not easy to transmit sufficient light to give good projections through a column of liquid of adequate length. By employing a tube eight inches long and two inches in diameter with plane glass ends, filled with oil of lemons (1 lb. of which costs about 10*s.* 6*d.*, and is just sufficient to fill such a tube) the object can however be effected. We introduce this next the polariser in lieu of the quartz. In the crystal stage we place the calcite or any other uni-axial crystal; and now introducing the quarter-wave plate between crystal and analyser, we obtain at once the double spirals. The liquid will also give the same phenomena as the quartz with other crystals, its slightly yellow colour only slightly interfering with the effect, for the same reason that the figures fail to appear in homogeneous light. Spirit of turpentine is free from this defect, but requires a column of almost unmanageable length.

Finally, it may be mentioned that Reusch's artificial quartz made of mica-films (§ 180), and Nörrenberg's artificial uniaxial crystals made of crossed micas (§ 199), give in each case similar results to the natural crystals. So also does a circular disc of unannealed glass in parallel light.

207. All the Phenomena due to Interferences of Waves.

—The student who has followed any considerable part of the experiments in this chapter, cannot fail to form a vivid idea of the *reality* of those invisible waves in the ether, whose interferences produce such complicated phenomena.

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[1] It is probable that a bar of heavy glass in the electro-magnetic field would give similar effects; but I have not been able to test the matter experimentally, and there is the very interesting difference between the behaviour of such a bar and other rotatory substances described in § 177. It seems scarcely probable that this difference would affect the above phenomena; but the settlement of that point would be interesting.

He will have grasped the fact, that in no case is anything visible or materially tangible in the crystal itself, *imaged* on the screen. The beautiful patterns have indeed a centre; but the centre of the crystal plates has absolutely nothing to do with that—let the pencil of light pass anywhere through his plate, and the effect is the same all over its area, so long as a given *direction* is preserved. In his combinations, beautiful designs have been produced, more resembling the richest Turkey carpets or Persian rugs than anything else; yet beyond the simple crossing of films in various ways, there is in the pattern nothing from the hand of man. And in his single crystal sections, by merely varying the polarised character of the light employed, he has produced at will either the simple rings with brushes, dislocated rings, unbroken rings with no brushes at all, or beautiful spirals. All the modifications are produced by transformations which simple mechanical analysis enables him to produce at will, in invisible and intangible ether-waves.

CHAPTER XV

POLARISATION AND COLOUR OF THE SKY.—POLARISATION BY SMALL PARTICLES

Polarisation of the Sky—Light Polarised by all Small Particles—Blue Colour similarly Caused—Polarisation by Black Surfaces—Experimental Demonstration of the Phenomena—Multi-coloured Quartz Images—Identity of all Radiant Energy.

208. **Polarisation of the Sky.**—On a clear day, in morning or afternoon, almost any of the colour phenomena we have now reviewed may be tolerably seen, by using the tourmaline close to the eye as analyser, and looking through the selenite or other object to the *sky* as polariser, in any direction at a tolerably wide angle with the direction of the sun, the maximum effect being at 90°. For instance, if the sun were due east, the greatest polarisation will be found anywhere in an arc extending due north and south. In the most favourable positions the quantity of polarised light is about one-fourth of the whole, and the rings in crystals can be seen very plainly with the sky as polariser. The direction of greatest polarisation of course depends upon the place of the sun; and upon this fact Sir Charles Wheatstone based the construction of a "polar clock," which gives the astronomical time by the effects of light from the sky upon slips of selenite in certain positions.

209. **Cause of the Phenomenon.**—Brücke and Professor Tyndall have beautifully explained not only this phenomenon, but also the blue colour of the sky, by proving experimentally that the light reflected laterally, or at right angles with the incident rays, from *any particles whatever sufficiently small*, is both polarised and of a blue colour. The blue colour is easily understood, if we remember what we have always found, that the blue waves are the shortest or smallest. Hence, from particles so small as to be in commensurable relations with them, the smaller waves may be wholly reflected, while larger ones are broken up or shivered into fragments, as it were, and so destroyed; just as—to quote Dr. Tyndall's own image—pebbles on a shore reflect small ripples entire, while they scatter and break larger ones. A secondary proof of this is ready to hand in the colour of the *transmitted* light. If it is partially robbed of its blue by these transverse reflections, the light transmitted ought to be more short of blue, or perceptibly yellowish, or in extreme cases reddish. That this is so, we see at every sunset, and also by the colour transmitted through any of the media presently mentioned.

210. **Polarisation by Small Particles.**—The polarisation at an angle of 90° with the incident ray, or at an angle of 45° with the surface of each minute spherical particle, has been considered a difficulty. Sir John Herschel remarked, that it supposes an index of refraction of unity; or that in the case of the sky, we have to suppose reflection *in* air *upon* air. There will be no difficulty in supposing this, if we conceive the molecules of air reflecting light at all; and the angle of 45° is exactly what we shall expect, if we receive the reasoning advanced in § 129. We have only to suppose that in any case of this scattered reflection, the reflecting molecules are too small to exert any refractive influence, and the whole difficulty is solved. While some, therefore, have considered polarisation by small particles to be a *fourth* method of polarising light, it

is not so considered here, but simply regarded as another case of polarisation by reflection.

211. **Black Surfaces.**—This seems also proved by, and is in fact the only method of explaining, the curious phenomenon of polarisation on analysation by a black surface, which was brought to my notice some time ago by Sir Thomas S. Bazley. It is stated in many works upon physical optics, that a black ribbon absorbs all the colours of the spectrum; but this is by no means practically the case in most instances, with the bright colours of the solar spectrum, which have a peculiar and attractive effect—of course owing to scattered reflection—on a black ground. Further, however: if we pass the light from the lantern through a polarising Nicol and a plate of selenite, and without any apparatus usually known as an analyser, receive the light at right angles on a dead-black card, the colour due to the selenite will appear, though it will not if the card be white.[1] Hence the black card itself acts as an analyser; and we can only explain this on the supposition that the black colouring matter, by absorbing or quenching the reflections from the flat surface as such, allows us to perceive the comparatively feeble results of the light reflected laterally from the small particles of carbon or other colouring matter. These particles are however so large, that it will be found the polarising angle considerably exceeds 45°. And the colour is of course comparatively feeble.

212. **Experimental Demonstration.**—Professor Tyndall precipitates fine vapours[2] in an exhausted glass tube with glass ends; but simpler apparatus will amply suffice for us. Small particles in water show the same phenomena, and either (1) a *very little* soap, or (2) a few drops of milk, or (3) about

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[1] That is, with the card in a normal position. An *inclined* white card analyses as a reflecting surface.

[2] Professor Tyndall has employed vapour from nitrite of butyl and hydrochloric acid, nitrite of amyl, bisulphide of carbon, and many other compounds. A friend of mine has obtained beautiful results from a whiff of tobacco smoke.

six grains of resin in an ounce of alcohol, or (4) about five grains of pure mastic in the same, will answer very well. On the whole I have myself found the best results, however, from a teaspoonful per gallon of the solution of coal-tar in alcohol known as Wright's Liquor Carbonis, stirred into filtered hot water. We may take a common glass lamp-chimney, 12 inches by 2 inches, grind one end flat and cement on it a flat glass plate, and fit a vulcanised stopper into the other. Fill carefully with the prepared water, *filtered* into the tube to remove dust, which mars the effect by reflecting common light. Mount the tube T in two semicircular notches of a cradle-stand,

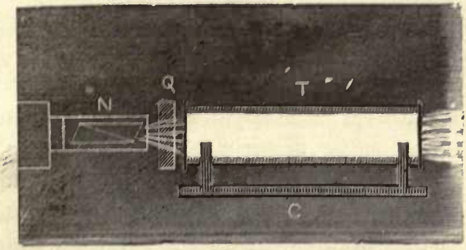

FIG. 206.—Experimental Tube.

as in C, Fig. 206, and adjust the tube horizontally in front of the plain optical objective—*i.e.* taking away the polariser—so as to throw the beam of light from the lantern along its axis.

If a dead-black board or sheet of card is held behind the tube, it is soon seen that it appears blue. The black back-ground is not even necessary, for the tube shines with a sky-blue light, unless the quantity of solid matter is much too large. It will also be readily seen, on looking as nearly as possible at right angles towards the tube through a Nicol, that most of the scattered light is "polarised"; for rotating the Nicol in the hand alternately quenches and restores it, and a selenite held between the tube and the Nicol at the eye, shows its usual colours.

We have already learnt, however (§ 125), that any apparatus which will act as a polariser, may also be employed as an analyser; and by polarising the light first, and using the tube as analyser, we can make the phenomena visible to a number of people at once. Add the Nicol, N (Fig 206), to the nozzle; the light from the lantern is now polarised, so that all who sit nearly at right angles with the tube can see the phenomena. As the Nicol is rotated, the light proceeding laterally from the tube is quenched or restored; and when *quenched* from a spectator on the same level, it is of course *brightest* to an eye looking down upon the tube from the top. Finally, if we hold a large quartz plate at Q, as the Nicol is rotated we get beautiful successions of colours in the tube.

213. **Multi-coloured Images.**—This is the simplest adaptation of the usual mode of performing this beautiful experiment; but there is a far better method—one not only easier, but which produces effects of surpassing brilliance and beauty, and which, as a truly magnificent lecture demonstration, may fitly conclude this work.[1] Procure a plain cylindrical glass jar on a foot, J (Fig. 207), 12 inches to 16 inches high, and 2 inches to 2½ inches diameter. Having cleaned it *bright*, filter the solution into that, and over it adjust the plane reflector, R, at an angle of 45°. The reflector throws the light from the Nicol, N, down through the fluid, which needs no glass plate, while the quartz can be laid on the top of the jar at Q. The first great advantage of this method is, that the audience all over the room see the effects perfectly, if about the same *height* as the jar; whereas with the other more usual plan, only

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[1] I was originally indebted for this beautiful modification of the experiment to Mr. John Thomson, of Dundee, a very able demonstrator. The beauty of the effect is a great tribute to his ingenuity, but the method has been so little known as to have been *re-discovered*, even since my publication of it, by Mr. G. J. Burch, B.A. (*see Nature*, Jan. 22, 1885).

those who can look nearly at right angles towards the tube perceive much of the phenomena, which depend upon an angle of nearly 90°. Still further, however: if two additional silvered mirrors, M M, about the height of the jar, by 6 inches or 7 inches wide, are arranged vertically behind the tube, inclosing it as it were within a right angle, though not touching, they give by reflection two additional images of the illuminated tube. Each of these, since the light leaves the tube from a different side, exhibits when the quartz is used *a different colour*, all three changing to successive colours with the rotation of the Nicol. With a large Nicol polariser embracing the full parallel beam from the lantern, the effect is finer still, and may be varied by employing a jar of greater diameter, and throwing the polarised light down through two apertures covered with quartzes of opposite rotations. In this case, in all but two positions of the analyser, there will be two beams

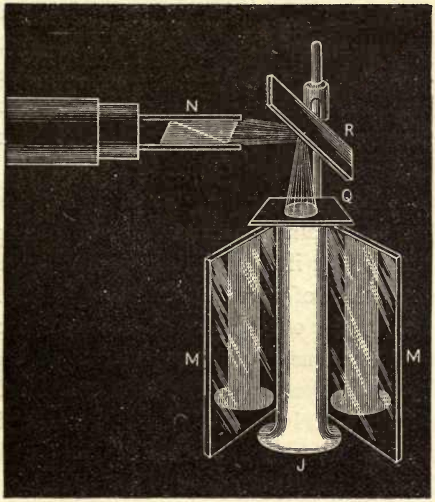

FIG. 207.—Multi-coloured Images.

of light in each image of the jar, glowing with different colours.

214. **Identity of all Radiant Energy.**—That heat rays and "chemical" rays are subject to the same laws as luminous rays, as regards reflection, refraction, and dispersion, has been already stated (§ 93), and is a familiar truth proved in every camera every day. It only remains to state that they obey also the laws of polarisation and double refraction. If the two beams which have passed through a double-image prism are tested with a thermopile, this is readily demonstrated, as is the fact that the ray is quenched whenever polariser and analyser are crossed. The actinic rays may be similarly tested with a sensitive plate, thus making the demonstration complete as regards all the rays of the visible and invisible spectrum, and proving that *the sole difference between any of them is in period of vibration;* some periods being more adapted to produce physical effects of certain kinds, and some of others. Captain Abney has shown that it is possible to obtain in a dark room a photographic image of a kettle heated far short of the luminous degree; or on the other hand, to impress a sensitive plate with a photographic image of large portions of the spectrum through an apparently opaque plate of the di-electric ebonite. And Professor Tyndall has proved experimentally that a plane-polarised beam of dark heat, filtered of all visible rays by a solution of iodine in carbon bisulphide, is rotated, like the luminous rays (§ 177), by a powerful electric current, or when the glass or other diathermous material is placed in a magnetic field. The far longer and slower waves of electric radiation obey the same laws, and when examined experimentally by proper appliances, exhibit essentially the same phenomena. From the quickest vibrations to the slowest, the series and the unity are unbroken; invisible waves of disturbance in the invisible Ether are alike at work, and constitute the physical basis of the whole of the phenomena.

CHAPTER XVI

LIGHT AS A SYMBOL

THROUGH all the experiments now described, we have discovered that the phenomena and sensations we know as Light and Colour, when traced back and examined, found their ultimate explanation in forms of Motion. We were shut up very early to that conclusion : we were absolutely compelled to travel in our thoughts from what we "saw" to something we could not see at all, and to form mental images of invisible waves, whose undulations were propagated with incredible swiftness all around us. Later on we found phenomena which appeared to reveal to us the actual *directions*, or orbits, of the vibrations in those waves; and applying to that hypothesis delicate and beautiful experimental tests, such as can be readily understood by any educated mechanic or other intelligent reader, we found our supposed orbits respond to those tests in every particular. The motions were, so far as we could judge from any possible mode of examination, modified, varied, resolved, or compounded, in all respects as our hypothesis led us to expect. This is the nature of the evidence, and we have thus reviewed in actual experiment the principal facts, on which is built up the Undulatory or Wave Theory of Light. The profoundest mathematical researches, applied to the most refined experiments varied in every possible way, have so far only confirmed that theory in every particular.

Let us fully grasp the grand conception; for there is no grander throughout the entire material Universe! All around us—everywhere—space is traversed in all directions by myriads of waves. Not more surely does a nail take up from a hammer the force of a blow, than does each particle of a mysterious and invisible Something, take up and pass on the motion of the preceding particle. Heat, Light, Colour, Electricity, Chemical Actinism,—all alike are simply disturbances in, or propagations of disturbance through, that Something which we call Ether. Invisible themselves, these wonderful motions make all Things visible to us, and reveal to us such things as are. Take away from the diapason of these invisible waves those of any given period; and if we lose the dazzling whiteness which results from them all in due proportion, we but increase the soft splendour of the phenomena, as the hues of the rainbow appear before our eyes. Let them clash against, oppose, and so destroy one another; and even their very interferences, though dark shadows may cross our vision, produce amidst these, forms and colours of almost unearthly beauty. Motion in the Ether accounts for all.

Here we have taken another step from the seen to the unseen; for we have conceived and named this Ether. The name is of course nothing; but we cannot do without the thing itself: we *must* conceive it. No eye has seen it; no instruments can weigh it; no vessel can contain it; nothing we have can measure it; yet it must be there. "There?"—yea, here also, and everywhere. Absolutely invisible, it yet is the sole key to all physical phenomena; and the most recent, most widely received, and altogether most probable theory about Matter itself, is that atoms are but Vortices in its infinite bosom. Ask for "absolute proof" of its verity, in the sense some attach to the word proof, and there is absolutely none; and there are even about the conception itself some stupendous difficulties. The physicist has to endow his Ether with the most contradictory properties. He conceives it as rarer and more subtle than the most exhausted atmosphere, with the principal properties of a perfectly elastic fluid; and yet, withal, the chief distinguishing property of a solid! All these paradoxes do not deter him; and he believes implicitly in this Ether he has never seen and never will see, simply because without it he can explain no solitary phenomenon around him, while with it and its motions he can explain everything. Light is thus, to him, a Revealer of all Nature, both visible and invisible.

The inquiry seems irresistibly suggested, whether the comparison and the analogy may not go further, and afford hint or revelation which goes deeper still. That inquiry is indeed strictly legitimate. If our Universe be in truth an objective and conditioned manifestation of any Absolute Foundation of all Being, it should be thus; the Actual ought, in its limited measure, however limited that measure may be, to reveal to us truly the Essential and Eternal. The student of Nature, at all events, does hold expressly that if she has any Author she must speak truly of Him, if she speak at all; and as for the so-called religious man, though any book can only take a secondary place in such an inquiry as this, he also admits that it ought to be thus, since his book actually says so. It is therefore a point of surpassing interest, whether as regards this question there is any definite agreement between these two, as to which physical Science can really have anything to say.

What then do we find? We are bound to ask the expounders of physical science first, for every reason. We inquire, therefore, what purely physical science, and experiment, and speculation—what *they* at present profess to teach us?

1. They tell us of an intangible, invisible Ether, which cannot be touched, or tasted, or contained, or measured, or weighed, but yet *is* everywhere; which contains within itself the potentiality of all the essential properties of Matter, fluid and solid; and yet which is not Matter, though it can communicate its own motions to Matter, and receive motions from it.

2. They speak to us next, according to the very widely

received Vortex Theory of Sir William Thomson,[1] something vaguely about this Ether taking Form. They suggest to us how Vortices in it may appear to us as those atoms of Matter which we do see, and feel, and handle; and which in this finite and conditioned Form *can* be limited, and contained, and measured, and weighed; in which the Ether may become, as it were, incarnate and embodied.

3. They tell us in the third place, of a mysterious Energy, which also takes protean forms. But in one form or other this Energy is doing all the physical work of the Kosmos; and by it even Matter itself is manifested to us, and becomes a part of our own consciousness.

And this is all; and Light embodies them all and reveals them all. It *is* Motion, a form of Energy; it is Motion *in* the Ether; and it is invisible, inconceivable, unknown to us, *unless* Matter, to make it visible, be in its path. There are these Three and these only; each distinct and separate; and yet the three making up One, a mysterious unity which cannot be dissolved.

So far the purely physical philosopher. Pondering attentively this wonderful triune conception which he has put before us, it will appear impossible that he at least should sneer at *any* other Trinity in Unity, seeing the kindred mystery in which he himself acknowledges that he dwells. Ether: Matter: Energy: no one of them can be conceived of apart from the others; yet each is separate and distinct. Take away either, and what becomes of the Universe, as we know it or can conceive it? And yet we say and think that this Universe is monistic—is one harmonious whole. The mystery of Nature is not only as great, but actually appears to be of the *very same kind*, as that which theologians have taught concerning the mystery of its Author.

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[1] It is almost unnecessary to say that this is only a hypothesis. And equally so to remark that in spite of difficulties, it makes more progress and receives further adherents every day.

For now we are at liberty to turn to the other, and ask him. He knew nothing of all this; never even dreamt of it, since it is the last growth of the nineteenth century. But, purely from an old Book he possesses, he too had, somehow or other, and long before the other, also gathered a conception, and even framed it into a theological formula. It will be at least interesting to see now what *his* conception is.

1. He tells us first, that he believes in an eternal, immortal, invisible, inconceivable, infinite Essence or Absolute, the one Source and Father of all.

2. He believes that this essential Being has in some mysterious way become embodied in a Second, in some inconceivable manner co-existent with, and yet derived from Him; who is the brightness of His glory and the visible Image of His substance;[1] and in whom and by whom all Things were made.

3. He affirms that these two work or act by and through an equally mysterious Energy; whose operations assume many forms; who does all things, alike in matter and in spirit; and who finally brings all conscious agencies that yield to Him, into harmonious relation and equilibrium with all that surrounds them.

That is the creed of the Christian, so much derided during the last twenty years. He also says and believes, like the other, that although he cannot explain it any more than the physical philosopher, these Three are One. Still more strange to say, he goes so far as to affirm that the Motions of the third originally produced that Light which we have found such a fascinating study; that to him, also, this Light is an express symbol and revelation of the Three; that it is even "as a garment" in which the Eternal and Invisible One clothes Himself, to be manifest to men!

This is but a suggestion. But *if* there should be reality and fact behind the belief of both parties as we have listened to

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[1] "The very Image [*or* impress] of His substance."—*R. V.*

them, is there not indeed here an obvious, deep, fundamental, marvellous agreement? More than this: if there should be true wisdom in what has been taught us by one of the most popular teachers of modern philosophy;[1] if it be true that "Religion and Science are therefore necessary correlatives;" if it be true that "Force, as we know it, can be regarded only as a certain conditioned effect of the Unconditioned Cause—as the relative reality indicating to us an Absolute Reality by which it is immediately produced;" if it be further true that "objective Science can give no account of the world which we know as external, without regarding its changes of form as manifestations of something that continues constant under all forms;" and if it be finally true as regards Spirit and Matter, that "the one is, no less than the other, to be regarded as but a sign of the Unknown Reality which underlies both;"—if these conceptions of one whom all regard as at least a great thinker, embody anything more than a foolish dream, is not this correspondence which we have found, precisely of the sort we ought to have expected to find?

The comparison and the inquiry appear in any case to be singularly interesting. The student of Nature, at least, should not object to it. And as for the other, he also may perhaps learn to hear of Matter possessing "the promise and potency of every form of life" without resentment, and to attach to the phrase a new meaning that might perchance be the basis of a great reconciliation, which has been long and sorely needed. He may perhaps learn to trust more fully what Nature and Science really have to say to him; and will at least have learnt in another way, that "the invisible things of Him since the creation of the world are clearly seen, even His eternal power and Godhead *being understood by the things which are made.*"

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[1] Mr. Herbert Spencer. All the sentences quoted are from *First Principles*, 3rd edition; and the last one cited is the final sentence of all in that remarkable volume.

INDEX

THE END

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4-1